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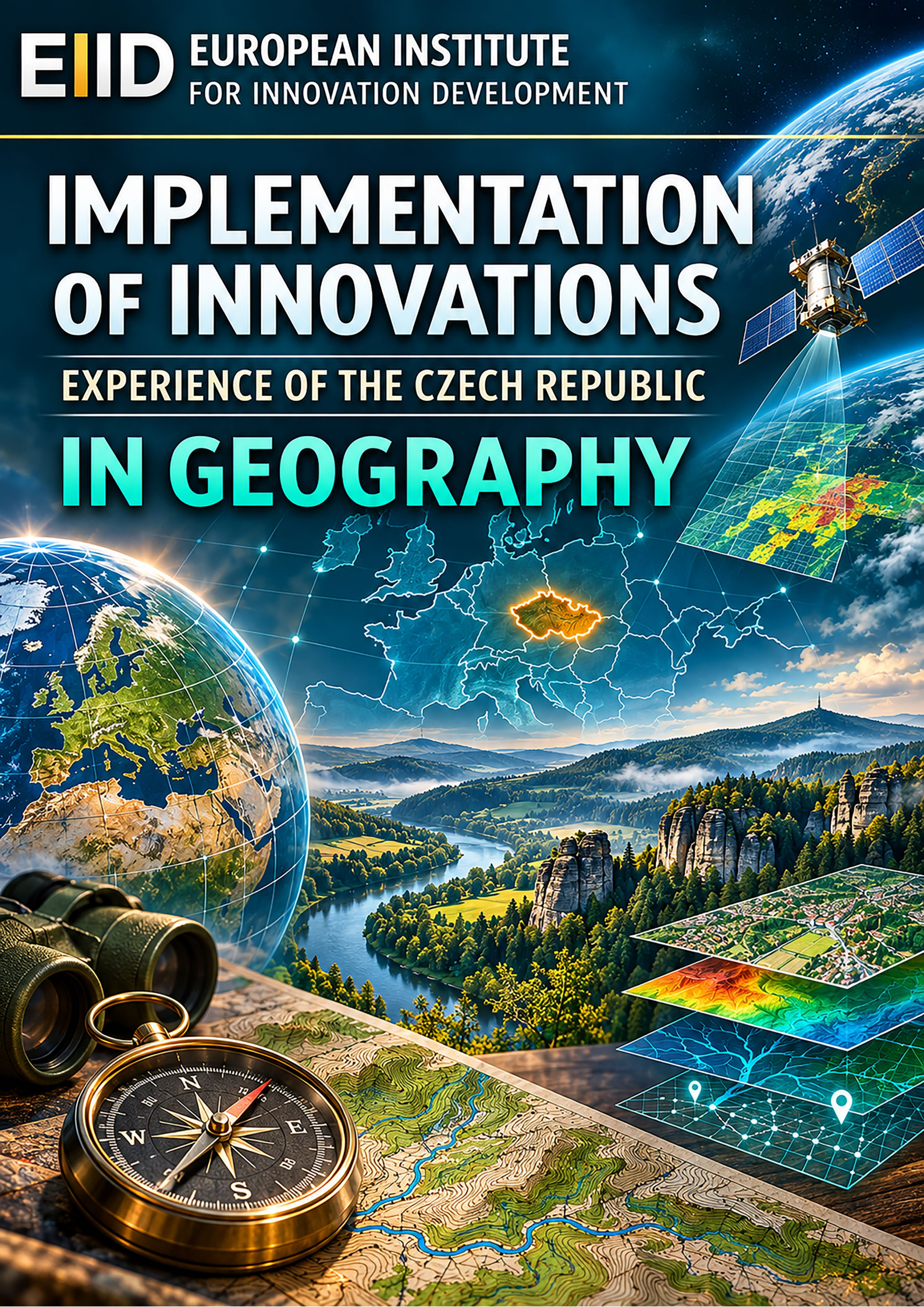
IMPLEMENTATION OF INNOVATIONS

EXPERIENCE OF THE CZECH REPUBLIC

IN GEOGRAPHY



EUROPEAN INSTITUTE FOR INNOVATION DEVELOPMENT



Implementation of Innovations in Geography

Experience of the Czech Republic

Dr. Alexander Buychik

Ostrava–Opava, Czech Republic

2026

Imprint
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Designed by Tuculart Studio.

Publisher:
Tuculart Edition (Tuculart s.r.o.), European Institute for Innovation Development, operated by the Tuculart Holding.

Edition:
Buychik, A. Implementation of innovations in geography: Experience of the Czech Republic. Ostrava, Opava: Tuculart Edition, European Institute for Innovation Development, 2026. — 573 p. (48.92 printed sheets)

ISBN 978-80-88474-59-3
DOI 10.47451/book-2026-23

For citation (in APA):
Buychik, A. (2026). *Implementation of Innovations in Geography: Experience of the Czech Republic*. Ostrava, Opava: Tuculart Edition, European Institute for Innovation Development.

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Introduction

Geography and Earth Sciences in Contemporary Czechia: Scientific Traditions, Spatial Change and Research Development, 1993–2025

The Czech Republic established in 1993 inherited a scientific community with long experience of studying a territory undergoing considerable economic and social change. Industrial districts were adjusting to new ownership and markets, while Prague and its surroundings were acquiring different relationships with the rest of the country. Changes in agriculture and settlement altered the use of land. The physical processes operating through these places continued on their timescales, occasionally making themselves felt with destructive force. Geographers and Earth scientists therefore encountered several kinds of change together. Their work concerned the transformation of the country, the behaviour of its natural systems and the changing means by which either could be understood.

This book examines the development of that research between 1993 and 2025. Its subject is the production of geographical and Earth science knowledge within the independent Czech Republic, including research undertaken by Czech institutions beyond the country's borders. Particular attention is given to the relationship between established scientific traditions and subsequent changes in methods, research questions and institutional arrangements. The central argument is that the period is best understood through the interaction of continuity and selective renewal. Different fields developed at different speeds, and scientific change often depended on maintaining observations, collections and expertise accumulated over much longer periods.

The scope of the volume requires some explanation. Geography encompasses the investigation of physical environments and the spatial organisation of human activity, although these branches draw on different forms of evidence and explanation. Geology and geodesy possess their own disciplinary histories and institutional foundations. Climatology and hydrology connect geographical enquiry with other natural sciences, while aerology is a specialised branch of meteorology concerned with observing and investigating the free atmosphere. These relationships justify a broad treatment of geography and Earth sciences, provided that the distinctive questions and standards of each field remain clear. Their connections are examined where they help explain how research developed.

The Czech setting offers substantial opportunities for such a study. The geological and geomorphological diversity associated with the Bohemian Massif and the Western Carpathians provides contrasting environments within a relatively compact territory. River valleys, karst systems and mountain landscapes preserve evidence of processes operating across widely different intervals of time. Some of these environments have also been altered by mining or other forms of intensive land use. This combination has encouraged research in which the reconstruction of natural history meets the interpretation of human influence. The

landscapes themselves consequently form part of the explanation for the scientific questions that have received sustained attention.

The chronological starting point identifies a change in statehood rather than the beginning of the disciplines considered here. Universities, scientific services and research institutes entered the independent republic with established personnel and substantial bodies of knowledge. The political opening after November 1989 had already changed the conditions of intellectual exchange. Its consequences were particularly significant for subjects concerned with social organisation and political space, where ideological constraints had affected the range of acceptable questions. Earlier natural science research also supplied methods and observations that remained indispensable. Understanding the period after 1993 therefore requires a measured account of inherited capabilities as well as the opportunities created by political change.

Institutional continuity could be precarious. The closure of the Geographical Institute of the Czechoslovak Academy of Sciences on 30 April 1993 was a significant disruption to the organisation of the discipline. University departments and professional networks subsequently carried responsibilities that could no longer be associated with that institute. Such changes matter because a scientific institution sustains relationships among people, teaching and research materials over time. Its formal disappearance may redistribute those relationships without bringing the underlying work to an immediate end. The history of Czech geography must accordingly follow research communities across organisational boundaries, rather than equating the history of the subject with the survival of a single institution.

The resulting research system included university departments, institutes of the Czech Academy of Sciences and organisations responsible for national scientific services. Universities connected enquiry with the education of successive generations of researchers. Specialised services-maintained observations and information needed for public decisions, while academic institutes pursued particular areas of fundamental and applied research. Their activities often overlapped. Prague, Brno and Ostrava appear repeatedly in this account, but the geography of the scientific community cannot be reduced to those cities. The regional distribution of institutions and their connections with specific environments and economic problems form an essential part of the analysis developed in the following chapters.

Long observation records deserve particular attention within this system. Hydrological and meteorological measurements become more useful when they can be compared across decades, yet their interpretation depends on understanding changes in instruments and recording practices. Geological archives and historical maps similarly acquire new uses when later questions are brought to them. Innovation can therefore involve the recovery and reassessment of existing material. The scientific value of a database or observation programme lies partly in the care with which continuity has been maintained. A history concerned only with newly established facilities would miss much of the work that makes contemporary research possible.

In physical geography, the period brought increasing opportunities to examine relationships among processes that had often been investigated through separate specialisms. Catchment

observations could be related to changes in vegetation or land use, while evidence from soils and sediments helped reconstruct earlier environmental conditions. More detailed spatial measurements extended the questions that could be asked in the field. The interpretation of those measurements continued to require close knowledge of particular places. This relationship between improved observation and informed geographical judgement is important throughout the volume, especially where a technically elaborate analysis must still explain why a process differs between neighbouring environments.

Research on land use provides a particularly clear meeting point between physical and human geography. The long historical perspective developed by Ivan Bičík and his collaborators relates changes in the Czech landscape to the economic and political circumstances in which land was managed. A field becoming woodland, or agricultural land being incorporated into a settlement, records decisions whose consequences may endure beyond the circumstances that produced them. Comparisons over time also depend on the consistency of the categories used to describe the land. This work demonstrates how historical records and spatial analysis can connect environmental outcomes with the changing organisation of society.

Geological research places these recent changes against a much longer history. Work on the Bohemian Massif, including investigations associated with Karel Schulmann and his collaborators, has contributed to explanations of continental collision and the evolution of the European crust. The importance of a national study area can thus extend well beyond the reconstruction of its geological past. Alongside such fundamental enquiry, the Czech Geological Survey continued to develop geological mapping and information services. Its adoption of that name in 2002 marked an institutional stage within an older history. The book considers how these scientific and public responsibilities developed together without assuming that they served identical purposes.

Geomorphology examines the evolution of the Earth’s surface and the processes through which particular landforms acquire their present character. In the Czech context, research on rivers and slopes has connected explanations of landscape development with questions of hazard. The synthesis edited by Tomáš Pánek and Jan Hradecký in 2016 illustrates the range of environments brought into a shared account of the country’s landforms. Geomorphological knowledge also supports the recognition of places whose scientific value merits protection. Its development therefore involves changes in explanation and measurement alongside a growing need to communicate the significance of landforms to people responsible for managing them.

Historical climatology offers another example of scientific continuity acquiring new analytical possibilities. Rudolf Brázdil and his collaborators have helped relate documentary evidence to the investigation of past weather and climate. A written account of a severe winter or a damaging flood has to be assessed in the circumstances of its production before it can contribute to a climatic reconstruction. The resulting enquiry draws on historical criticism as well as natural science. Its value lies partly in extending the period over which variability and extremes can be examined. It also asks how earlier societies experienced weather, bringing the physical event into relation with the conditions that made people vulnerable to it.

The atmosphere also requires observations that cannot be obtained from instruments at ground level. Aerological work at Prague-Libuš supplies measurements of conditions above the surface, including temperature, humidity and wind, together with observations of ozone. The station's place within the international observation network makes a local measurement useful to a much wider community. Aerology is consequently treated here as a specialised component of atmospheric science with its own requirements for instrumentation and data quality. Its historical importance is best judged through the development and use of those observations, rather than through the expectation that every field should possess the same kind of independent institutional structure.

Hydrology brings the interpretation of physical processes into particularly direct contact with public needs. The severe floods of 1997 and 2002 made the assessment of exceptional events an urgent research problem. Yet an account of hydrological development must also consider less conspicuous changes in water storage and availability. Work on snowmelt, groundwater and catchment behaviour helps explain how water moves through environments that differ in geology and land cover. A damaging flood and a prolonged water deficit require different forms of analysis, although both depend on a sound understanding of the water balance. The chapters on water research examine how these questions shaped measurement, modelling and the interpretation of risk.

The establishment of Intersucho in August 2012 illustrates the connection between research and a continuing information service. The project drew on earlier work on drought monitoring and climatology and brought together expertise from several institutions. Its significance for this book lies in the way a scientific problem acquired an operational form through sustained cooperation. Information about drought must be produced at intervals and spatial scales that are useful to its intended users, while remaining open to scientific scrutiny. This requirement gives practical importance to questions about data quality and communication. It also shows why the history of research must consider what happens after a method has first been developed.

Economic geography encountered a different set of rapidly changing relationships after the end of state socialism. Foreign investment and industrial restructuring altered the position of Czech firms within wider production systems. Research by Petr Pavlínek and Pavla Žížalová, e.g., examined relationships between foreign and domestic firms in the automotive industry and the conditions under which knowledge and other benefits might pass between them. The presence of investment alone could not explain its regional consequences. Attention had to be given to the capabilities of firms and to their roles within production networks. Such questions encouraged a closer relationship between detailed empirical investigation and theories of uneven economic development.

Regional change also required explanations that could accommodate differences within the national territory. Martin Hampl and Miroslav Marada's work on metropolitan development examined changes in the concentration of population and economic activity during the transformation period. A national description could conceal the different experiences of metropolitan and other regions. These differences mattered to the formulation of research questions as well as to public policy. The development of Czech economic geography is

therefore considered through the changing geographical relationships it sought to explain. Theoretical renewal becomes most informative when it can be connected to the interpretation of a specific pattern or process.

Social geography directs attention to how such changes are experienced within settlements and everyday life. Research on residential segregation, including the work of Luděk Sýkora, has examined the relationship between inherited urban patterns and divisions emerging under new social conditions. Housing and residential mobility give spatial expression to differences in resources and opportunities. These processes may operate within a single city while also reflecting national institutions and international movements of people. Their investigation requires a careful relationship between spatial evidence and the social mechanisms used to explain it. The book follows the development of these questions while keeping the history of geographical research distinct from a general history of Czech society.

Political geography acquired a more explicit institutional presence during the period. At the University of Ostrava, a master's programme in political and cultural geography was accredited in 2000, followed by a doctoral programme in 2007. These developments provide a concrete setting in which to examine the renewal of a specialism concerned with political space. Changes in borders and territorial relationships supplied questions that extended beyond the immediate circumstances of Czech independence. The subject also maintained close connections with cultural geography and regional studies. Its treatment in this volume recognises those relationships while allowing political geographical enquiry a distinct place within the wider history of the discipline.

Geodesy supplies a further perspective on the relationship between national capability and international science. Permanent GPS observations at the Pecný observatory began in September 1993. Regular contributions to the International GNSS Service followed in 1995, and inclusion in the EUREF Permanent Network followed in 1996. These connections made measurements from a Czech station part of the maintenance and interpretation of wider reference systems. They also supported research on changes in position and on atmospheric parameters. In this field, scientific development can be traced through the precision and comparability of measurements and through the networks that make those measurements useful beyond their original location.

Cartography and geoinformatics connect many of the fields examined here. A map brings selected observations into a common spatial frame, while a geographical information system permits relationships among different kinds of spatial data to be investigated. The growth of digital observation has widened those possibilities and increased the importance of understanding how data were obtained. Greater detail does not remove problems of classification or uncertainty. This book therefore considers geospatial technologies through their consequences for scientific practice. The relevant questions concern which relationships became observable, how explanations were tested and what kinds of geographical judgement continued to be required.

The territorial reach of Czech research provides a useful corrective to assumptions based on the country's size or location. Masaryk University's Johann Gregor Mendel station on James

Ross Island was completed in 2006 and officially opened in February 2007. Its subsequent programme has included the investigation of polar climate, glaciers and environments exposed by retreating ice. Such work depends on sustained logistical and scientific commitments. It also demonstrates that the geographical limits of a state do not determine the limits of its research. The account presented here includes overseas work where its institutional connection with Czech science can be established and its contribution to the development of a field can be assessed.

The evidence for this history takes several forms. Scholarly publications reveal research questions and methods, while institutional records help establish the circumstances in which particular programmes became possible. Observation histories and the documentation of scientific services provide another perspective, especially where important developments occurred through gradual improvement rather than a single conspicuous discovery. Czech and English sources form a substantial part of the material, supplemented where relevant by scholarship in other European languages. Foreign studies of Czech territory are considered alongside work produced within Czech institutions, with attention to the different roles these sources play in explaining the national scientific community.

The interpretation of this material requires care with dates and categories. A study of a much earlier geological episode may constitute an achievement of the period after 1993, whereas an inherited instrument may underpin observations made throughout the same period. The date of the research must therefore be distinguished from the age of its subject matter. Institutional names also change, and present arrangements cannot simply be projected backwards. The closing date of 2025 identifies the limit of the historical account. Where a programme continued beyond that year, its place in the book rests on activity and results that belonged to the period under examination.

The organisation of the volume combines a chronological account with separate histories of the principal fields. The opening parts establish the political and institutional circumstances in which research developed. Subsequent parts examine the questions, methods and achievements of particular disciplines, including the work of identifiable research groups and scholars. This arrangement allows differences in pace and emphasis to remain visible. Connections among the fields are explored where a shared problem brought researchers together, while detailed explanations are located within the discipline to which they chiefly belong. The aim is to make comparison possible without repeatedly narrating the same institutional events.

As material for an international distance internship, the book is intended to support informed comparison with other research environments. Readers should be able to identify how a scientific question was framed and what evidence was needed to investigate it. The Czech experience is particularly useful where long observational traditions meet changing social demands or new technical possibilities. Its relevance to another country will depend on the circumstances in which knowledge is to be used. The chapters that follow therefore give attention to the conditions under which research became possible and to the reasoning through which observations were turned into scientific understanding.

Part One

Historical Evolution of Geography and Earth Sciences in the Czech Republic, 1993–2025

1989 as an Intellectual Watershed and 1993 as a New State Framework: Scientific Continuity and Institutional Reorganisation

The history of geography and the Earth sciences in the independent Czech Republic begins with two changes that must be distinguished. November 1989 altered the political conditions under which knowledge could be produced, discussed and taught. The establishment of the independent state on 1 January 1993 changed the national framework within which scientific institutions operated. Between these dates, researchers were already reconsidering the organisation of their work. The distinction matters because it prevents the founding of the republic from being mistaken for the founding of its scientific community. Czech geography entered 1993 with substantial intellectual resources, but with the institutional arrangements sustaining some of those resources under active revision.

This inheritance had itself been shaped by political change. Geography at Charles University had developed through successive organisational forms and political regimes, as the historical study by Leoš Jeleček, Pavel Chromý and Jiří Martínek demonstrates. The continuity of a discipline depended on teachers, research programmes and educational relationships as well as on the survival of a departmental name. Successive political interventions affected who could teach and which lines of enquiry could flourish. Yet geographical knowledge accumulated through these disruptions. A history beginning in 1993 consequently needs to distinguish the circumstances in which an earlier finding was produced from its subsequent scientific usefulness. Rejecting the political authority of the former regime did not require the rejection of every observation or analytical achievement associated with its institutions.

Political control also shaped individual careers. The University of Ostrava's departmental history records that Radim Prokop was removed from the geography department in 1971 and returned after 1989. His experience gives a human scale to the expression 'intellectual watershed'. Restrictions on employment interrupted teaching and the transmission of expertise long before they appeared as gaps in a bibliography. Reinstatement reopened a professional relationship, although the years lost could not be recovered.

Professional organisations participated in the opening rather than merely responding to decisions made elsewhere. In December 1989, the geographical society, chaired by Václav Král, supported the students' strike. An extraordinary assembly in November 1990 adopted the name Česká geografická společnost, or Czech Geographical Society. Its own historical account subsequently records the closure of the Academy's Geographical Institute on 30 April 1993 and the loss of material and organisational support that followed. Taken together, these

episodes reveal the society's double position: it could express the collective judgement of geographers, yet it also depended on a particular institutional setting. Political emancipation and organisational security did not necessarily advance together.

Academic freedom acquired an explicit legal foundation before the dissolution of Czechoslovakia. The Higher Education Act of 4 May 1990, effective from 1 July, guaranteed freedom of scientific research and publication, teaching and learning, and the election of academic self-governing bodies. It also protected the expression of philosophical and religious views and excluded the establishment and activity of political party organisations within higher education institutions. These provisions changed the legitimate basis of university authority. Scientific disagreement could be defended as part of academic work, while participation in governance became a recognised institutional principle. For geography, the significance extended beyond the removal of particular forbidden subjects. It concerned who could determine a research agenda, revise a curriculum or challenge an established explanation.

Legal freedom and intellectual renewal nevertheless operated on different timescales. A statute could remove a formal restriction immediately; a revised course required preparation, and a new research programme required people able to sustain it. In social and political geography, the questions themselves could be affected by the changing meaning of property, public authority and national territory. In physical geography, geological research or hydrological observation, the first task might instead be to preserve a programme while its administrative surroundings changed. These differences should not be reduced to a division between disciplines that changed and disciplines that continued unchanged. Research could retain its instruments and field sites while acquiring a different explanation of its purpose.

The restoration of Masaryk University's name in 1990 illustrates the relationship between symbolic recovery and institutional continuity. From 1960 to 1990, the university had borne the name of Jan Evangelista Purkyně. Its archive places the return to the Masaryk name alongside the student mobilisation of November 1989, including the formation of strike committees at the Faculty of Arts. The change made an older institutional identity publicly available again. It did not establish a new university or erase the scientific work undertaken under the previous name. For the historian, this is a useful distinction: the recovery of a tradition can be a consequential act even when teaching rooms, collections and much of the academic staff remain in place.

At Charles University, the Department of Social Geography and Regional Development describes its present organisational form as dating from the changes after 1990. Its history nevertheless reaches back through the earlier organisation of economic and regional geography, including the work associated with Jaromír Korčák. The post-1989 department therefore combined a revised institutional identity with an inherited intellectual lineage. The pairing of social geography with regional development also provided a way of relating geographical explanation to questions about the future organisation of territory. A departmental title alone cannot establish the extent of theoretical change. It does, however, identify the setting within which established regional knowledge could be brought into conversation with changing social questions.

The emergence of the University of Ostrava in 1991 followed another route. Geography moved from the former pedagogical institution into the new Faculty of Science. The university's account also notes that its environmental division, established in 1987, was dissolved after the political transition. Geographers from the division moved into private business, while biologists joined the biology department. University expansion thus coincided with the redistribution of expertise already assembled for environmental enquiry. The separation of physical and human geography into departments came later, in 1995. The institutional map of Czech geography was still being redrawn after independence.

These university histories suggest several meanings of scientific continuity. A scholar might resume teaching after exclusion; a university might recover an older name; a department might acquire a different remit without abandoning its predecessors. None of these processes can be measured adequately by counting new institutions. Conversely, the retention of an institution's name does not establish that its intellectual life remained the same. For the period around 1993, the more revealing questions concern the movement of people and the authority to organise their work. This approach allows a restored institution and a newly constituted university to be considered within the same history without assuming that their experiences were interchangeable.

Reform of the Academy was likewise under way before Czech independence. Its official historical account identifies Otto Wichterle, president of the Czechoslovak Academy of Sciences from 1990 to 1992, with the initiation of substantial changes. That account acknowledges the ideological pressures of the preceding period while recognising that significant scientific work and international connections had survived within it. The point is especially relevant to the Earth sciences, whose post-1989 development depended on accumulated expertise. The Academy could not renew itself merely by repudiating its predecessor. It had to determine which capabilities should be sustained, how researchers should participate in decisions and which organisational arrangements remained defensible.

Marek Blažka's history of public support for Czech research provides a more detailed view of this transition. After November 1989, demands from individual Academy institutes were coordinated through civic initiatives, followed by a chamber of elected institutional representatives. In February 1990, a colloquium at Smolenice brought together representatives of universities, Academy workplaces, sectoral institutes and the education ministries of both republics. By 1991, discussions of restructuring explicitly connected institutional support with assessment of scientific performance and envisaged independent foreign expertise. Reform therefore involved changes in representation and in the grounds on which an institute could justify its resources. These developments also show why institutional contraction cannot be explained solely as an administrative consequence of the new Czech state: the reconsideration of the research system was already proceeding within Czechoslovakia.

The Czech National Council adopted Act No. 283/1992 on 6 May 1992. According to the Academy's historical chronology, the Czechoslovak Academy ceased to exist on 31 December 1992, the date on which the Czech Academy was established. The legislation therefore belonged to the final year of the federation, with the new institutional framework in place at its

end. Czech independence on the following day gave that framework a different constitutional setting. The preparation of the Academy had already crossed an important legal threshold.

The founding Academy Assembly met on 24 and 25 February 1993. Its resolution envisaged a modern system of autonomous scientific institutes, with thematic specialisation, interdisciplinary relationships and cooperation with universities and applied research. This was a programme for the new Academy rather than evidence that every desired relationship had already been achieved. Nevertheless, it clarifies the terms in which institutional legitimacy was being reconstructed. A specialised institute was expected to justify its scientific role while remaining connected to work beyond its own boundaries. For geography and the Earth sciences, this raised a practical question: whether a particular line of enquiry required a separate institute or could be sustained within a differently organised research environment.

The distinction between institutional legitimacy and disciplinary value is essential when considering the Geographical Institute's closure. The loss of an organisation is a documented event; the disappearance of a field is a much larger claim, requiring different evidence. Geography continued to possess university departments, professional relationships and bodies of research material. Yet their existence should not make the closure seem inconsequential. An institute provides time, employment and administrative support within which cooperation becomes habitual. When that setting is removed, the continuation of research depends on arrangements that must be negotiated elsewhere. Scientific continuity is therefore an outcome requiring explanation, rather than a reassuring assumption that can be made whenever some former employees remain professionally active.

One route of reorganisation led through the Institute of Geonics. Its predecessor, the Mining Institute in Ostrava, had become an independent Academy institute in 1982. From 1990, its research conception broadened: expertise in mineral extraction was extended towards other uses of the Earth's crust, including underground construction and storage, and the environmental consequences of human activity. The Mining Institute was renamed the Institute of Geonics on 1 April 1993, before the closure of the Geographical Institute later that month. The two events were distinct decisions within a wider redistribution of research responsibilities.

A Brno branch concerned with environmental geography was incorporated into the Institute of Geonics during this transformation. Geographical enquiry was thereby placed alongside research with roots in mining science and geomechanics. A recognisable research orientation continued within a host institute whose remit had itself widened. This arrangement preserved a particular field of work; it did not reproduce the full disciplinary coverage of the former Geographical Institute. Following the Brno branch into its new setting reveals one specific mechanism through which research could continue after organisational disruption.

The movement of library holdings offers a quieter but unusually tangible example of continuity. The Geography Library at Charles University records that it received collections from the dissolved Academy institute in 1993. Its chronology also notes the renewed acquisition of high-quality foreign specialist literature from 1990. These developments joined inherited materials to a widening range of current scholarship. A collection transferred to a university library could

support readers who had never belonged to the institution that assembled it. The organisational history of a body of literature thus outlived the organisation itself. Such transfers matter because access to earlier maps, studies and periodicals affects the questions that later researchers can investigate without having to reconstruct an entire documentary foundation.

The reorganisation of geological research followed a different sequence. The Institute of Geology's official history records its incorporation into the Institute of Geology and Geotechnics in 1979 and its re-establishment as a separate institute in 1990. Here, a disciplinary institution was restored before the new national framework took effect. This is a useful counterpoint to the experience of geography in 1993. Institutional reform did not proceed through one uniform policy translated into identical outcomes across the Earth sciences. A separate identity could be recovered in one field while another lost its principal Academy institute. The difference directs attention towards the particular history and scientific responsibilities of each organisation, rather than towards a single general verdict on the reform.

The geological service must also be distinguished from the Academy's Institute of Geology. The institution now known as the Czech Geological Survey adopted the name Český geologický ústav in 1990; the present Czech name, Česká geologická služba, dates from 2002. These are stages in the history of a geological organisation with roots in 1919, not alternative names for the Academy institute. Maintaining the distinction is necessary when tracing the continuity of public geological information alongside academic research. Institutional names in present-day directories can otherwise produce a misleading picture of the early 1990s. The same territory was being investigated through organisations with different histories and responsibilities, and those differences remained relevant after independence.

Taken together, these cases reveal a research system whose geography cannot be reconstructed from the Academy alone. Universities connected research with teaching, while specialised organisations preserved other forms of expertise and documentation. The existence of several institutional settings could provide alternative homes for scientific work. It could also leave responsibilities divided in ways that required coordination. A discipline's position therefore depended partly on its relationships with neighbouring fields and on the purposes for which its knowledge was needed. The changes around 1993 sharpened the importance of these relationships, although they did not create them for the first time.

The organisation of funding introduced a further dimension. The Czech Science Foundation began its activities in 1993 and became an important national mechanism for supporting basic research through grants. Its establishment should be distinguished from the much older existence of scientific institutions and from the reform initiatives already under way within them. A grant supports a specified programme of enquiry; an institution also sustains facilities, employment and the conditions under which programmes can be developed. These functions are related but cannot simply substitute for one another. For the history considered here, the significance of 1993 lies in the emergence of a national funding body alongside the reorganisation of institutional research. Its subsequent operation and disciplinary effects require assessment over the longer period examined in the following section.

Long-running observation creates a particularly demanding test of the relationship between organisational change and scientific continuity. The interpretation of a river record, a sequence of atmospheric soundings or repeated geodetic measurements depends on knowing how the observations were made. A change of political system cannot divide a physical process into scientifically self-contained periods. Nor can a new instrument be treated as though it were merely an administrative replacement. Where equipment or procedures change, the history of measurement becomes part of the evidence. The continuity that matters is therefore more exacting than the uninterrupted existence of an institution: it includes the ability to establish what successive measurements mean and whether they can be compared.

Aerological observation in Prague illustrates how technical change crossed the political chronology. The Czech Hydrometeorological Institute's account of basic upper-air measurement dates the introduction of the Finnish Vaisala DigiCORA MW11 receiving system and Vaisala radiosondes to 1992. This development preceded the independent republic. The programme concerned observations of atmospheric conditions above the surface, acquired through instruments carried by meteorological balloons. It depended on specialist operational knowledge as well as equipment. In this instance, 1993 inherited a recently modernised practice rather than inaugurating it. For a historical account of aerology, the important sequence is consequently the sequence of instruments and observations, considered alongside the institutional chronology without being forced to coincide with it.

Geodesy provides a closely dated example from the first year of independence. At the Geodetic Observatory Pecný, permanent GPS observations at the GOPE station began on 7 September 1993 using a Trimble 4000 SSE receiver. The precision of the date helps separate an identifiable technical development from the broader narrative of political transition. Continuous satellite observations introduced a new kind of observational record at an established scientific workplace. They should not be attributed to independence merely because they began in the same year. Explaining their place in Czech geodesy requires attention to the observatory's technical work and to the wider development of satellite methods. The later international integration of the station belongs to the next phase of this account.

The distinction between these observational histories and the institutional crisis in geography is analytically useful. Several kinds of change could occur simultaneously without sharing the same cause. A university might revise its governance, a research group might change employer and an observatory might introduce a new measurement system. Each event could affect future scientific possibilities, but through a different mechanism. Treating all three as examples of modernisation would conceal more than it explained. The task is to identify the decisions and inherited resources that connected a particular change with subsequent research, rather than to infer scientific improvement from the general direction of political history.

The dissolution of Czechoslovakia likewise requires attention to institutions that already existed on both sides of the new international boundary. The Geographical Institute of the Slovak Academy of Sciences traces its foundation to 1943 and its incorporation into the Slovak Academy to 1953. Its own history treats 1990 as the beginning of a new phase associated with changed research organisation and grant support. These dates make clear that Slovak

geography was not created through a division of Czech institutions in 1993. The two scientific environments entered separate state frameworks with older and partly distinct institutional histories. Their relationship after separation must consequently be investigated through continuing scholarly connections and subsequent cooperation, rather than assumed to be either complete continuity or complete rupture.

For economic, social and political geography, the altered state framework also became part of the subject matter. A formerly internal territorial relationship could acquire an international dimension, while regional development had to be understood within changed arrangements of public authority. Such questions did not make earlier knowledge of settlement or regional organisation irrelevant. They changed the conditions under which it could be interpreted. The distinction between evidence and the framework used to explain it became especially important: an inherited description of a settlement system might remain informative even when the political assumptions surrounding its original use no longer held. Intellectual renewal could therefore proceed through the re-examination of established material as well as through the investigation of newly emerging processes.

A contemporary publication shows that this reconsideration was already taking place at the threshold of independence. Writing in German in 1993, Jiří Hrůza and Alois Andrle examined the settlement of the Czech Republic in relation to the political and economic changes of the preceding years. They connected settlement change with the responsibilities of spatial planning, infrastructure provision and environmental improvement. Their account is valuable here as evidence of the questions being posed at the time. It reveals an attempt to interpret inherited urban and rural structures under changing conditions. The authors' emphasis on the country's renewed position within Europe should be read as part of that contemporary interpretation, rather than adopted uncritically as a complete explanation of scientific change.

The opening of intellectual exchange also needs to be understood as a working practice. The ability to obtain literature, assess an unfamiliar approach and relate it to local evidence could matter more for an individual investigation than a general declaration of international orientation. This helps explain why library acquisitions and curricular revision belong within a history of scientific development. They were among the means through which a wider intellectual environment became usable. At the same time, the appearance of a foreign publication or a new organisational title does not by itself demonstrate the adoption of a new theory. Such claims have to be tested against the questions researchers asked and the explanations they actually produced.

The years from 1989 to 1993 thus combined a rapid alteration of legitimate authority with a more selective reconstruction of scientific organisation. The clearest evidence concerns specific changes: academic freedoms received statutory recognition, university identities and departmental arrangements were revised, and the Academy acquired a Czech legal framework. Research groups and collections could continue across institutional boundaries, while particular organisations disappeared or recovered their independence. Technical programmes followed their own sequences. These developments established the circumstances from which later research proceeded, but they did not determine its results.

The longer history after 1993 must explain how the opportunities and losses of this interval were translated into sustained enquiry.

At the end of 1993, Czech geography and the Earth sciences therefore occupied a new state framework without having become a new scientific community. The intellectual opening of 1989 had made inherited authority contestable; institutional decisions had redistributed the means of research. What followed depended on whether expertise could be retained, younger scholars trained and credible programmes supported in the resulting settings. This is the point of departure for the next stage of the history. The development of research between 1993 and 2003 can be understood only by following those capabilities into the work they made possible, with equal attention to what continued and to what had to be rebuilt.

1993–2003: Post-Socialist Transformation, Research Reorientation and the Development of New Scientific Networks

During the first decade of Czech independence, the transformation of the country became a sustained research problem. Changes that had initially appeared as political events acquired recognisable spatial consequences, which could be compared between regions and followed through time. Geographers investigated the changing uses of urban space, the movement of people and the reorganisation of economic activity. In the Earth sciences, established knowledge was put to work on environmental questions, while new observational arrangements extended the scale of enquiry. The period from 1993 to 2003 was particularly significant for the relationships through which this work proceeded. Domestic research projects, international partnerships and regular exchanges of observations supplied different means of turning intellectual freedom into continuing scientific activity.

Martin Hampl's work illustrates the effort to relate contemporary transformation to a more general geographical explanation. In a 1996 article, he examined empirical changes in Czech society alongside questions about geographical regularities, the relationship between social and geographical structures, and uneven development. The formulation retained a concern with the organisation of society in space while asking how that organisation behaved under changed conditions. Transformation was therefore available for theoretical investigation as well as description. Its unevenness mattered: a national change of economic system did not imply an identical course of development in every locality. The resulting research problem concerned the interaction between inherited spatial arrangements and processes whose effects were still unfolding. This supplied a connection between an established Czech geographical tradition and the analysis of the post-socialist period.

Urban research made these relationships visible at a finer scale. In his 1999 study of Prague, Luděk Sýkora distinguished the commercialisation of the historic core, the revitalisation of parts of the inner city, and residential and commercial suburbanisation towards the metropolitan edge. These processes involved different locations and different mechanisms. Their coexistence made the city difficult to explain through a single account of movement

towards a market economy. Sýkora also drew attention to the slower pace at which settlement structures changed compared with political and economic institutions. Buildings and the arrangement of neighbourhoods carried earlier decisions into the new period. Prague thus became a setting in which the consequences of reform could be investigated through the persistence and selective alteration of its material geography.

By 2003, suburbanisation had become a research agenda with an explicit public dimension. Sýkora's article on its social consequences considered the expansion of metropolitan activity in relation to experience in North America and Western Europe. The concern was partly anticipatory. Dispersed development could leave enduring economic, social and environmental consequences, making it necessary to investigate the process while its forms were still being established. This approach moved geographical enquiry beyond the documentation of new construction. It asked how emerging settlement patterns might influence subsequent social life and what kinds of intervention could affect their development. International comparison supplied questions and concepts, while the Czech case required attention to its own settlement inheritance. The changing metropolitan fringe became a place where geographical research could inform discussion of future conditions.

Economic geography similarly widened the relationships through which Czech territory was interpreted. Petr Pavlínek's 2003 study of the automotive components industry examined restructuring through foreign direct investment and the incorporation of suppliers into European and global production networks. It considered the effects of Volkswagen's investment in Škoda on supplier relationships, including demands concerning quality and cost. The relevant geographical connection extended beyond the location of a factory to the firms and decisions on which its production depended. Pavlínek was working at the University of Nebraska at Omaha, a reminder that research on Czech transformation also developed through scholarship based abroad. Such work belonged to a wider discussion in which Czech industrial experience helped explain the changing organisation of production in Central Europe. It should be distinguished from research produced entirely within Czech institutions, while remaining part of the intellectual environment with which they engaged.

Population movement provided another way of investigating the country's changing position. Dušan Drbohlav's 2002 analysis asked whether Czech migratory trends were converging with or diverging from those of the developed world, particularly Western Europe. He combined quantitative comparisons with questions about migration policy and relationships among immigration, socio-economic development and majority attitudes towards minorities. His conclusion favoured convergence. The importance of the study for this period lies also in the design of the comparison. Migration was being examined as part of the changing organisation of Czech society and its international relationships, with several kinds of evidence brought to bear on the same question. This helped establish a field in which the counting of movements could be connected with the circumstances governing them.

Political geography acquired a broader framework of teaching and debate in the volume Stát, prostor, politika, edited by Petr Jehlička, Jiří Tomeš and Petr Daněk and published in 2000. Its contributions addressed uneven development, globalisation, environmental politics and the organisation of political space. The range included electoral systems and international

integration, bringing questions often treated separately into a shared geographical setting. Environmental politics was particularly revealing because ecological relationships do not necessarily coincide with the territorial divisions through which states act. The volume made these questions available within Czech academic discussion and provided material through which students could encounter competing approaches. Its breadth is evidence of an expanding intellectual agenda; the subsequent depth of particular research traditions has to be assessed through their own publications and projects.

The changing relationship between society and territory also encouraged work across the boundary between human and physical geography. Land use was especially suited to this purpose. It recorded the practical consequences of economic and political decisions while remaining connected with soils, water and vegetation. Researchers could therefore examine the landscape as evidence of social change without treating its physical properties as incidental. The attraction of the subject lay partly in the possibility of comparing recent developments with a much longer history. A change observed during the 1990s could be assessed against the arrangements inherited at the beginning of the decade.

A 1996 paper by Ivan Bičík and his collaborators presented a research programme using land-use data for 1845, 1948, 1990 and 1995. The inclusion of the last date allowed the early transition to be considered within the same analytical framework as earlier changes. The researchers used an index of change to compare districts and tested the approach at cadastral level in the Semily district. They also related the programme to interdisciplinary questions identified by the International Geographical Union. Historical material was thus being reorganised for a contemporary comparative purpose. The connection between national evidence and an international research agenda was particularly productive here: a geographically detailed Czech record could contribute to questions about how societies altered their environments over time.

The international publication of work by Bičík, Leoš Jeleček and Vít Štěpánek in Land Use Policy in 2001 extended this line of interpretation. Their account related long-term land-use change in Czechia to social driving forces across the nineteenth and twentieth centuries. This temporal reach gave the recent transition a historical setting. It also made the country a case through which relationships between political and economic circumstances and environmental outcomes could be discussed more widely. The sequence from assembling comparable records to explaining their changes is an important feature of the decade. New research questions drew value from older documentation, while publication in a specialist international journal placed the interpretation before readers concerned with other territories.

The published studies also show how national funding supported the reorientation of research. Hampl’s theoretical investigation and the 1996 land-use study acknowledged support from the Czech Science Foundation, while subsequent work on the Morava floods was supported by the Academy’s grant agency. These acknowledgements identify concrete programmes through which researchers could develop questions over time. They connect the institutional history of funding with the work appearing in scientific journals. The coexistence of national support and international publication also matters: an investigation could be financed domestically while contributing to a discussion whose participants were located much further afield.

In geology, the completion of national geological and hydrogeological mapping at 1:50,000 in 1995 provided a substantial common basis for further enquiry. This achievement brought a long programme of territorial investigation into the early years of the independent state. Comparable coverage made it possible to relate local observations to adjoining areas and to use geological information across different public and scientific purposes. Its significance for the decade was therefore partly cumulative. Research reorientation could draw upon a detailed representation of the subsurface that had required sustained work to assemble.

Environmental monitoring developed through a complementary approach. The geological survey, then known as Český geologický ústav, established the GEOMON network of small forested catchments in 1994. Repeated observations of water and ecologically important chemical elements supported biogeochemical investigation. Questions concerning atmospheric deposition and ecosystem condition connected geology with hydrology and the study of soils. A catchment provided a setting in which inputs and outputs could be considered together. Such work required the continuity of measurements through changing environmental conditions, giving the new decade responsibilities that would remain scientifically useful well beyond it.

The floods of July 1997 brought a different tempo of environmental change. In northern Moravia and Silesia, river channels and floodplains could be altered within an event whose effects demanded immediate field investigation. Miloš Hrádek's study, published in 2000, combined interpretation of landforms observed after the flood with aerial photographs and other reports. It examined channel widening, erosion and the movement and accumulation of material, with differences between the Eastern Sudetes and the Western Carpathians. Human alterations to channels and floodplains also influenced the effects. The study demonstrated how an exceptional event could become evidence about geomorphological processes. Its explanation required close attention to what the water had changed on the ground, alongside an understanding of the conditions in which those changes occurred.

Research at the Brno branch of the Institute of Geonics brought the physical and social consequences into the same investigation. In 2000, Antonín Vaishar, Pavlína Hlavinková, Karel Kirchner and Jan Lacina reported work in four model areas affected by the Morava floods. They considered changes in riverbeds, slope movements and biota alongside the consequences for communities. Their interpretation connected the distribution of damage with settlement patterns formed during industrialisation and urbanisation. This made the flood a geographical problem extending across the event itself and the earlier occupation of the floodplain. The research also considered adaptation to risk and the location of structures. It gives a concrete example of the environmental geography sustained at the Brno workplace after the organisational changes described in the preceding section.

The August 2002 floods in Bohemia again required meteorological and hydrological knowledge to be assembled around a major event. A government resolution of 7 October 2002 provided the basis for a comprehensive assessment, whose meteorological and hydrological components were made available by the Czech Hydrometeorological Institute. The structure of the assessment joined the causes and extremity of rainfall with the course of the flood, the estimation of flows and the performance of reporting and forecasting services. It also included

the effect on groundwater. This organisation of enquiry shows the range of scientific responsibilities mobilised by a flood. Explanations had to connect atmospheric conditions with the behaviour of catchments and with the information available to people responsible for responding.

Historical climatology enlarged the period over which damaging atmospheric events could be investigated. In 2003, Petr Dobrovolný and Rudolf Brázdil published a study of documentary evidence for strong winds associated with convective storms in the Czech Republic since 1500. The work drew upon the historical climatological database developed at Masaryk University. It turned dispersed written observations into evidence that could be compared through time, while retaining the need to assess what an account could reliably establish. The age of the events should not obscure the contemporary scientific achievement. Collecting and interpreting historical evidence extended the questions that could be asked about extremes beyond the duration of an instrumental series. This was a methodological contribution to environmental research, grounded in the close reading of records as well as the analysis of their geographical and temporal distribution.

Meteorological modelling developed through a more directly operational form of international cooperation. An agreement between RC LACE and Météo-France in 1994 supported work on ALADIN, a numerical prediction system for a limited geographical area. In June 1998, ALADIN/LACE operations moved from Toulouse to Prague. Until December 2002, the Czech Hydrometeorological Institute hosted a regional centre where scientists from participating services worked for extended periods; Radmila Brožková led this centralised phase. The centre depended on continued connections with the global ARPEGE model in France. Its history also records the practical pressures of sustaining a shared workplace, including costs and the difficulty of accommodating the requirements of every participant. A decentralised phase began in January 2003, retaining coordinated research while assigning operational systems to the member services. The network therefore changed its organisation within the decade in response to the experience of working together.

The scientific purpose of such cooperation was connected with the resolution at which atmospheric processes could be represented. A model applied over a limited area could describe finer circulation features than a coarser system covering a much larger domain, although the additional detail increased computational demands. The model also required information about conditions beyond that area. Regional specialisation consequently depended on a wider forecasting system. For meteorology and its observational branches, including aerology, this relationship placed local technical work within an international chain of observations and calculation. It helps explain why model development and the exchange of expertise were closely connected during the period.

In the solid Earth sciences, CELEBRATION 2000 organised cooperation around a shared field experiment. Seismic observations made in June 2000 were intended to investigate the crust and uppermost mantle across Central Europe, including the Bohemian Massif. The experiment brought together European and North American institutions, with Czech researchers participating in a network whose observational profiles crossed several countries. The Geophysical Institute’s report for 2000–2001 described interlocking profiles totalling about

8,900 kilometres and explained how recorded wave arrivals were used to investigate the distribution of seismic velocities. A technical account published in 2003 by Aleksander Guterch and an international team, including Aleš Špičák, set out the experiment for a wider scientific readership. Here, the scale of the geological question helped determine the scale of cooperation: national observations acquired explanatory value through their relationship with measurements across a much larger region.

The experiment also clarifies the distinction between collecting a major dataset and completing its interpretation. An extensive recording campaign could establish the basis for investigations continuing beyond 2003. Its place in the present period rests on the organisation of the experiment, the observations themselves and the analyses already under way. Later geological models belong to subsequent stages of this history. Recognising this sequence allows an early investment in cooperation to receive its proper place without transferring later findings into the decade in which the data were first acquired.

Geodesy developed an enduring form of international participation through regular observation. The GOPE station at the Geodetic Observatory Pecný began its regular contribution to the international IGS observing system in 1995 and joined the EUREF Permanent Network in 1996. The significance went beyond the presence of satellite equipment at a Czech site. An observation became part of a continuing system in which measurements from several locations could be used together to maintain reference frames and investigate changes in position. Participation depended on sustained operation and the comparability of the resulting data. The network gave a national scientific workplace a continuing international function, through the regular provision of observations rather than a single joint campaign.

Geographical information systems created another setting for contact between specialists. At VSB–Technical University of Ostrava, the GIS Ostrava symposium began in 1994, followed by the GISáček student conference in 1998. The latter provided a meeting place for students from the Czech Republic and Slovakia. These events helped establish regular occasions for discussing methods and applications in a field developing across disciplinary boundaries. Their importance should be assessed at the scale of professional practice: researchers and students needed opportunities to compare ways of representing, processing and interpreting geographical information. A recurrent meeting could support that exchange even when participants worked on different substantive problems. The continued Czech–Slovak setting also shows how an academic relationship could be maintained within the separate state frameworks.

Publication offered a further means of sustaining a geographical community and reaching readers elsewhere. The opening volume of Moravian Geographical Reports was dated 1993 but appeared for the Prague conference of 1994. In its editorial, Jan Munzar linked the journal with the earlier publishing tradition of the Academy's Geographical Institute. The initiative brought the Brno branch of the Institute of Geonics together with Moravian university geographers, while welcoming contributions from further afield. English was chosen to reach foreign readers and support exchanges with other scientific collections. The editorial also addressed the costs of the undertaking: departmental contributions would have to be supplemented by sales and

other external income. The new outlet consequently depended on an editorial and financial commitment as well as the intention to communicate internationally.

Prague also became a meeting place for wider scholarly communities. The 1994 regional conference of the International Geographical Union brought approximately 1,200 geographers to the city. In 2003, the second international conference of the European Society for Environmental History was held there, with about 350 participants and involvement from historical geographers at Charles University. The two events indicate different dimensions of international contact: a broad disciplinary gathering and a meeting organised around the historical relationship between people and environments. They also show the contribution of Czech geographers to organising scholarly exchange. Hosting a conference did not in itself guarantee a lasting research partnership, but it created opportunities for comparing evidence and identifying questions that could be pursued together.

Teaching cooperation helped maintain contact between such events. From 1994, the Department of Social Geography and Regional Development at Charles University worked with Dartmouth College on courses for American students concerning Czech and Central European transformation and integration into European structures. This was a specific educational relationship, with the changing region itself as its subject. It required Czech experience to be explained to readers and students approaching it from another academic setting. Alongside research publication, such teaching contributed to the circulation of geographical interpretations and to the personal relationships through which later academic work could develop.

European research cooperation was becoming more formally organised before the end of the decade. The Czech Republic participated in the European Union's Fifth Framework Programme from 1999, while it was still preparing for membership. The chronology is important. European scientific integration was already proceeding through research arrangements before accession changed the country's wider political position. Participation created a further setting in which institutions could seek partners and develop common projects. Its effects on individual geographical and Earth science fields varied and require examination through specific programmes. Nevertheless, it placed the partnerships established during the 1990s within a broader framework that would become increasingly important after 2004.

By 2003, several distinct forms of scientific connection were operating together. Urban and migration researchers contributed Czech evidence to comparative debates; environmental investigators assembled long records and examined the effects of exceptional events. Observation networks and common experiments required more tightly specified technical cooperation, while journals and teaching partnerships sustained other kinds of exchange. These arrangements brought different obligations. A joint publication might grow from a limited investigation, whereas an operational forecasting system or permanent station required dependable work from day to day. Their coexistence helps explain how internationalisation became embedded in scientific practice during the decade, without implying that every field followed the same route.

The resulting research environment was more diverse than the one visible at the beginning of independence. Transformation had become a subject of geographical explanation, environmental events had generated investigations crossing disciplinary boundaries, and Czech workplaces had assumed identifiable roles in international scientific systems. These developments rested on expertise and records inherited from earlier periods, but they also established relationships through which new enquiries could continue. The close of 2003 marks a useful point at which to recognise those achievements on their own terms. The expansion of opportunities associated with European Union membership belongs to the next phase; the networks through which Czech researchers would encounter it were already taking shape.

2004–2013: European Integration, International Cooperation and the Expansion of Research Infrastructure

The Czech Republic joined the European Union on 1 May 2004 with scientific relationships already extending well beyond its borders. Accession changed the political setting of those relationships and enlarged the framework within which research could be supported. During the following decade, geography and the Earth sciences benefited from investment in facilities and from more organised forms of cooperation. The effects appeared in different places: at established observatories, in university research groups and at newly developed environmental research centres. Their common significance lay in the questions that researchers could investigate together. The period from 2004 to 2013 saw an expansion of scientific capacity whose value depended on connecting equipment and observations with sustained programmes of enquiry.

European support operated through instruments with different purposes. Framework Programme projects organised cooperation around particular research questions, usually for a defined period. Structural funding could support the development of the facilities in which research would continue. In the Czech Republic, the Operational Programme Research and Development for Innovation, associated with the 2007–2013 programming period, supported modern equipment, new research workplaces and increased capacity in higher education. These forms of support could complement one another, but they created different commitments. A consortium needed a coherent common investigation; a new facility also needed staff and resources for its subsequent operation. The practical relationship between these commitments shaped the scientific consequences of investment.

The distinction is important when interpreting the closing year of this phase. The dates of a funding period did not necessarily coincide with the completion of every project it supported. Some facilities being developed in 2013 belonged to programmes continuing into later years. Their appearance in this account therefore rests on the work already undertaken, rather than on capabilities established afterwards. This chronology also helps explain why scientific development could proceed unevenly within the same institution. An existing team might be

producing results while the equipment intended for its next investigations was still being installed.

CzechGlobe provides a particularly clear example of the relationship between institutional renewal and investment. The project to develop a centre for studying the impacts of global climate change began on 1 December 2010. The Global Change Research Centre of the Academy of Sciences was established in Brno in January 2011, drawing upon research previously conducted at the Institute of Systems Biology and Ecology. Its development brought together questions concerning the atmosphere, ecosystems and society. The programme included the modelling of climatic extremes and regional change, investigations of carbon exchange, and methods for assessing environmental impacts. Its intended breadth connected several fields considered separately elsewhere in this book. Geography supplied ways of relating processes observed at particular sites to environmental differences across a larger territory.

The infrastructure programme reflected that scientific breadth. Ecosystem observation stations and experimental facilities were designed to connect measurements of environmental conditions with explanations of ecological responses. Remote sensing offered another scale of observation, while modelling could explore relationships beyond an individual field site. A measurement of exchange between vegetation and the atmosphere still had to be understood in relation to the ecosystem in which it was made. CzechGlobe therefore concerned the organisation of evidence across scales as well as the acquisition of instruments. The project remained under development at the end of 2013, with completion extending beyond the present period.

Some of the expertise incorporated into this environment had acquired an international setting earlier in the decade. The history of CzechGlobe’s airborne activities records the acquisition of an AISA Eagle hyperspectral scanner in 2004, followed by participation in a European Space Agency PECS project from 2005 to 2008 and the FP6 HYPER-I-NET network from 2006 to 2009. Hyperspectral observation separates reflected radiation into many narrow spectral bands, providing information relevant to the condition of vegetation and other surface materials. The historical sequence joins an identifiable instrument with programmes through which its scientific uses could be developed. It also places an important limit on the account: the later Flying Laboratory of Imaging Systems began operating in 2015, and its full capabilities should not be projected back into this decade.

The formation of the InterSucho team in 2012 shows how the expanding research environment could support a more specific problem. Scientists at CzechGlobe worked with colleagues at Mendel University and Masaryk University in Brno under the leadership of Miroslav Trnka. The collaboration included Ulf Büntgen from Switzerland and Michael Hayes from the United States, bringing experience from established research on environmental history and drought. The initiative connected an emerging Czech programme with expertise beyond Europe as well as within it. At this stage, the important development was the assembly of a multidisciplinary team concerned with monitoring drought and understanding its consequences. The later operation and expansion of drought information services belongs to the next phase of the history.

Another form of expansion concerned the integration of facilities already distributed across the country. Government support for CzechGeo was approved on 15 March 2010. The project sought to connect permanent observatory measurements and temporary monitoring of geophysical fields within a national research infrastructure. It was closely associated with the European Plate Observing System, EPOS, whose preparatory phase began in November 2010. The value of this arrangement lay in the possibility of bringing observations into a wider scientific relationship. A recording made at one station could contribute to an investigation requiring measurements from several places and specialisms. During this period, EPOS was still being prepared; its later institutional form and services should be distinguished from the cooperation being organised in 2010–2013.

Distributed infrastructure presents a different problem from that of a single laboratory. Observing sites retain their particular locations because those locations matter to the phenomena being measured. Integration therefore depends on the treatment of data and on agreements governing work at different sites. Its scientific usefulness rests on the combination of observations to answer questions exceeding the reach of an individual station. CzechGeo made these relationships part of the organisation of national geoscience.

The interpretation of observations collected before 2004 continued to yield important results within this enlarged environment. In 2005, Pavla Hrubcová and an international group of collaborators published their investigation of the crust and uppermost mantle of the Bohemian Massif using CELEBRATION 2000 data. The work combined seismic modelling with additional constraints, including gravity information, to investigate a region divided into tectonic units with different histories. The resulting models distinguished three types of transition between the crust and mantle. In the central Moldanubian unit, the boundary was particularly pronounced and reached a depth of about 39 kilometres, while the southeastern Moravian part displayed a thicker transition zone. These differences connected the deep structure with the tectonic history of the massif. The earlier field experiment thus supported a later explanatory achievement. A large cooperative dataset created possibilities whose realisation required further analysis and could sustain scientific relationships after the field teams had dispersed.

Research on environmental hazards brought several of these observational practices into close contact. A study published in 2013 by Burda and his collaborators investigated the reactivation of a landslide at Eisenberg in northern Bohemia in January 2011. Long-term geodetic measurements, geomorphological mapping and geophysical profiling contributed different evidence about the site. The analysis associated progressive deformation with the collapse of an old mine gallery, while the immediate reactivation followed a rise in the water table induced by rapid snowmelt during winter warming. This was a precise explanation of interacting conditions at a particular place. It illustrates the contribution of sustained measurements to distinguishing the circumstances that prepared a slope for failure from the event that triggered movement.

In geodesy, the development of CZEPOS extended satellite positioning services across the national territory. Initial stations were installed in 2004, and the provision of data and real-time services followed in 2005. This widened the practical availability of a reference system beyond the scientific observatories discussed in the preceding section. Surveying and other forms of

spatial measurement could draw upon a maintained network rather than depend entirely on a separate local reference arrangement for each task. The scientific significance was partly infrastructural: observations of the landscape and its changes could be located within a consistent geographical framework. That framework required continuing technical attention, since the usefulness of a positioning service depends on the reliability of the coordinates and corrections it supplies.

The CZEPOS chronology records the modernisation of receivers and antennas in 2011–2012, including support for GPS and GLONASS and preparation for Galileo. Established equipment was being adapted as the technical environment changed. This was a form of infrastructure development less conspicuous than the opening of a centre, but important to its users. The continuing performance of geodetic services helped make measurements comparable over time and between sites.

The airborne laser scanning undertaken between 2009 and 2013 supplied another important body of geographical observations. Its data formed the basis of DMR 4G, the fourth-generation digital terrain model of the Czech Republic, representing surface heights on a regular five-metre grid. The acquisition programme created a common basis for examining the form of natural and modified terrain. Such information could support investigations in which small differences in surface elevation affected drainage or the interpretation of landforms. Its usefulness depended on processing and on an understanding of the limitations of the resulting representation. The measurement campaign belongs to this period of investment, while the subsequent use and further development of national terrain data continued into the following phase.

Geological information was being connected through European cooperation as well. OneGeology-Europe began in 2008 with the aim of making geological mapping accessible through a common European framework. The Czech Geological Survey was responsible for a multilingual metadata catalogue. Such work addressed a practical obstacle to the use of information assembled by different national services. Researchers needed to know what a dataset described, how it had been produced and whether it could be related to material from elsewhere. The catalogue’s significance therefore concerned the intelligibility of the information accompanying a map. The development of European data relationships depended on that less visible work alongside geological interpretation and cartographic production.

The national assembly of geographical knowledge was also expressed through substantial cartographic publications. The Landscape Atlas of the Czech Republic, prepared for publication in 2009 under the editorial direction of Tatiana Hrnčiarová, Peter Mackovčin and Ivan Zvara, related the country’s physical setting to its historical and social development. Its preparation required cooperation across the subjects represented in the volume. A contemporary announcement by the Ministry of the Environment also described the creation of new vector layers for maps at 1:500,000 because an appropriate current state map base was unavailable. The atlas consequently involved the preparation of shared geographical material as well as its presentation. This was an achievement of coordination that made a broad body of knowledge available for comparison within a common cartographic work.

Human geography produced a complementary synthesis in the Atlas of Socio-spatial Differentiation of the Czech Republic, edited by Martin Ouředníček, Jana Temelová and Lucie Pospíšilová and published in 2011. Its thirteen connected chapters and thirty-seven large maps presented evidence at the level of individual municipalities. Topics included population characteristics, employment, accessibility and services, alongside migration and suburbanisation. Analytical texts and supporting material were provided in Czech and English. The combination made the geographical detail accessible to readers examining the Czech case from elsewhere. It also connected a long programme of data collection with questions about the quality of life in particular communities, giving social geography an extensive common resource for further investigation.

These atlases occupied a different place in research from a funded observatory or laboratory, but they addressed a related need for organised evidence. A common map base and a documented set of categories allow findings produced by several specialists to be considered together. The process can expose differences in the spatial units or definitions through which a phenomenon has been recorded. Cartographic synthesis therefore requires intellectual decisions as well as technical production. In this period, major national publications made the relationships between those decisions and the resulting account of Czech territory particularly visible.

European projects also extended the comparative setting of research on regional development. DERREG, which ran from 2009 to 2011, investigated the implications of globalisation for rural regions and sought to develop an interpretative model useful to regional actors. Coordinated by Aberystwyth University, the consortium included Mendel University in Brno alongside partners from other European countries. The Czech contribution therefore belonged to a programme whose questions extended beyond a national account of transition. Rural development was being considered through the relationships connecting regions with wider economic and social processes. The collaboration provided an identifiable institutional setting for comparing those relationships, while retaining attention to the circumstances of the regions being investigated.

Economic geography developed more detailed evidence about the position of Czech industry within international production. Petr Pavlínek and Jan Ženka's 2011 study evaluated upgrading among 490 Czech automotive firms using financial indicators for the years 1998–2006. Its interpretation drew on the perspectives of global value chains and global production networks. The geographical question concerned the quality and character of industrial change within those relationships, rather than the location of investment alone. The work illustrates a methodological development in the study of transformation: a substantial body of information about individual firms could be used to examine a process often discussed through national industrial totals. It also shows how established Czech research questions were being pursued through concepts shared with a wider international field.

International collaboration in urban geography supported conceptual work as well as empirical comparison. In 2012, Luděk Sýkora and Stefan Bouzarovski published a framework distinguishing institutional, social and urban transformations in post-communist cities. Their argument explained why the completion of major institutional reforms did not mean that urban

change had ended. Land-use patterns and other material arrangements continued to adjust through processes with their own timescales. The collaboration linked Charles University with the University of Birmingham and placed experience of post-communist cities within a general discussion of urban change. Czech geographical research was thus contributing ways of interpreting a wider regional experience, with the changing Czech city providing more than an illustrative national case.

Hydrological research and flood management likewise acquired a European setting. FLOODsite operated from March 2004 to February 2009 under the Sixth Framework Programme, with coordination by HR Wallingford in the United Kingdom. Its consortium included the Czech company GEO Group, and pilot applications included sites in the Czech Republic. The programme joined the investigation of physical flood processes with social vulnerability and risk management. The combination continued questions raised by the floods of the preceding decade while placing them within a collaborative effort to develop comparable methods. Czech participation also illustrates the involvement of specialised organisations beyond universities and Academy institutes in the production and application of geographical and hydrological knowledge.

The research problem concerned the relationship between an event and its consequences. A description of the magnitude of a flood could not by itself establish the harm it would cause in a particular settlement. FLOODsite's executive summary accordingly treated risk through the sources of the hazard, the pathways by which water reached exposed places and the consequences for people, property and the environment. This formulation brought physical and social evidence into the same analytical structure. Its importance for the period lay in the effort to make such relationships usable within methods of assessment and decision support, while recognising that river systems and the responsibilities associated with them crossed national borders.

Climatology offered a particularly clear scientific result from the combination of evidence across countries. In a paper published in the 2010 volume of Climatic Change, Petr Dobrovolný and an international team reconstructed Central European temperatures back to 1500. Documentary series from Germany, Switzerland and the Czech Republic were combined with eleven instrumental records, with other European material used for cross-checking. The work addressed inconsistencies in early measurements and evaluated the reconstruction through the period in which documentary and instrumental evidence overlapped. Within the resulting record, 1988–2007 was identified as very likely the warmest twenty-year interval, with uncertainty explicitly considered. The contribution depended on the compatibility of evidence assembled through several national traditions. Czech historical climatology thereby became part of a reconstruction at a larger geographical scale.

The territorial reach of research also expanded beyond Europe. Masaryk University's Johann Gregor Mendel station on James Ross Island in Antarctica was completed in 2006 and formally opened in February 2007. It provided a continuing base from which Czech researchers could work in a polar environment. Its place in this history concerns an extension of the conditions under which field research could be sustained, rather than the application of an exclusively European funding model. A remote station required reliable support before observations could

become a continuing scientific record. It added a geographical setting whose seasonal conditions and logistical demands differed substantially from those encountered at domestic field sites.

A 2013 paper by Pavel Prošek and his colleagues examined the station’s technical facilities, with particular attention to its energy requirements. Wind turbines, solar thermal panels and diesel generators formed part of a system that also had to address water and waste management. These arrangements were integral to the possibility of maintaining scientific activity at the site. They also made the research base itself a subject of investigation. The paper is useful evidence of the work required to convert a national commitment to polar science into an operating facility. The resulting capacity depended on maintenance and informed use of local conditions as well as the original construction.

Across these examples, the expansion of infrastructure changed relationships within the Czech research system. A national positioning service could support measurements undertaken by several disciplines; a geological catalogue could make data held elsewhere intelligible; a field station could sustain repeated investigation in an unfamiliar environment. These connections gave specialised work uses beyond the institution that performed it. They also created obligations extending beyond an individual research grant. Technical staff, data stewardship and the continuity of observation became part of the explanation for the scientific possibilities available to researchers.

Investment also needed to be considered in relation to the people able to use it. Instruments do not determine the questions asked of their observations, and the existence of an international consortium does not make its evidence automatically comparable. Researchers had to develop working relationships through which expertise could be exchanged and methodological differences resolved. The studies discussed here show several ways in which that happened, from the integration of documentary climate series to the interpretation of seismic records. The value of new capacity became visible through particular investigations, whose reasoning could be assessed independently of the scale or cost of the facilities supporting them.

By the end of 2013, Czech geography and the Earth sciences possessed a wider range of research settings and more organised connections between them. European cooperation had supported common investigations, while national and European resources had helped sustain and expand the means of observation. Major publications also assembled evidence for readers working across disciplinary or national boundaries. Some developments were already producing identifiable results; others were establishing capabilities whose fuller use lay ahead. The following period would bring those investments into contact with further changes in digital methods and with growing demands for explanations of environmental and social change.

2014–2025: Methodological Diversification, Digital Technologies and Research on Environmental and Societal Change

Between 2014 and 2025, Czech geography and the Earth sciences acquired a wider range of ways to observe change and to question its causes. Facilities developed during the preceding decade began supporting sustained investigations, while satellite archives and smaller airborne instruments made repeated observation more practicable. Human geographers examined movements recorded through mobile networks and invited residents to contribute their own geographical knowledge. These developments changed the evidence available to researchers, although their intellectual consequences depended on how that evidence was interpreted. The period was marked by growing methodological diversity, accompanied by renewed attention to the limits of measurement. Drought, flooding and industrial restructuring brought environmental questions into closer contact with livelihoods, public policy and the uneven geography of opportunity.

The consolidation of CzeCOS illustrates how earlier investment developed into a continuing research resource. Hosted by CzechGlobe, the infrastructure connected ecosystem observation with experiments and airborne remote sensing. Its place in the national infrastructure roadmap was renewed through updates in 2015, 2018 and 2023. Access arrangements allowed researchers outside the host institution to apply to use its facilities through scientific projects. CzeCOS also provided Czech connections to European infrastructures concerned with carbon observation, ecosystem experiments and airborne environmental research. For geography, this arrangement widened the possibilities for relating local processes to regional environmental conditions. Its importance lay partly in the availability of facilities to different research groups, allowing an established observation site or experimental system to support questions beyond its original programme.

Within this environment, measurements of exchanges between ecosystems and the atmosphere gave physical geography a closer relationship with biogeochemistry. CzechGlobe's ecosystem stations used the eddy covariance technique, which estimates exchanges through rapid measurements of air movement and the properties of the air being transported. Such observations could be considered alongside meteorological records and information about vegetation. A forest's response to a dry season could consequently be investigated through measured exchanges of carbon, water and energy, as well as through changes visible in its canopy. The geographical task remained one of interpretation across different settings. Measurements from a particular stand acquired wider meaning when researchers understood the environmental conditions and land management that made that site distinctive.

Airborne research also acquired a more differentiated set of instruments. CzechGlobe's Flying Laboratory of Imaging Systems began operating in 2015. Its subsequent history included the start of the ESA FlexSense project in 2018, the operation of a drone carrying hyperspectral and thermal sensors from 2020, and cooperation with the Italian National Research Council on PRISMA satellite calibration activities in 2023. These developments brought observations at different spatial scales into the same research environment. Hyperspectral measurements

record reflected radiation in numerous narrow bands, while thermal observations describe another aspect of surface conditions. Connecting them required attention to calibration and to the circumstances of each flight. The scientific gain came from relating those measurements to processes in vegetation and the landscape, rather than treating an additional image as an explanation in itself.

Satellite research made the selection and comparison of measurements a subject of methodological enquiry. In an article assigned to the 2025 volume of AUC Geographica, Daniel Paluba, Bertrand Le Saux, Francesco Sarti and Přemysl Štych investigated Sentinel-1 radar parameters using 600 validated broad-leaved and 600 coniferous forest areas in Czechia. Several derived parameters conveyed nearly identical information. The study therefore examined which measurements were most useful for distinguishing forest types and following seasonal behaviour. It also introduced a freely available Google Earth Engine procedure combining radar and optical time series with topographic and weather information. This work illustrates a more selective approach to growing data archives. Research progressed through testing what different variables contributed and providing a reproducible means of assembling them.

At the scale of individual channels, repeated drone surveys gave geomorphologists another means of measuring landscape adjustment. Jakub Miřijovský of Palacký University and Jakub Langhammer of Charles University published a study in 2015 based on four surveys of the Javoří brook in the Šumava Mountains between May 2013 and September 2014. Photogrammetric reconstruction produced terrain models and corrected images at approximately two-centimetre resolution. Comparing successive surveys allowed the authors to examine bank retreat and the volumes affected by erosion. The analysis followed changes initiated by the June 2013 flood into the following year. It joined a detailed record of channel form to a sequence of hydrological events, enabling researchers to distinguish the immediate effects of flooding from subsequent adjustment within the same stream reach.

Machine learning extended the possibilities of such observations while making validation especially important. A 2021 study by Theodora Lendzioch, Jakub Langhammer, Lukáš Vlček and Robert Minařík combined field measurements at the Rokytka peat bog with information derived from drone imagery. Random forest models used surface form, vegetation and temperature information to estimate groundwater level and soil moisture. The authors tested predictions by withholding locations from model training and mapped the areas in which the models could reasonably be applied. Performance varied substantially between the predictions examined. This was an instructive development in physical geography and hydrology because it treated uncertainty as a spatial property of the result. A continuous prediction map could then be read together with evidence about where the available observations justified confidence.

The relationship between field knowledge and automated analysis consequently became more demanding. A detailed image could reveal a riverbank or a vegetation pattern, but it could not by itself establish why the feature had changed. Differences between survey dates might reflect environmental processes, seasonal conditions or measurement procedures. Researchers needed stable reference points and appropriate comparisons, together with

observations on the ground. Across these studies, digital methods strengthened established geographical practices of revisiting places and comparing conditions through time. They also made the consequences of methodological choices more visible. The resolution of a surface model and the area over which a statistical relationship remained reliable became part of the explanation that accompanied the findings.

Drought research brought this concern with evidence into direct contact with agricultural losses. Jan Meitner and his co-authors reported in 2023 a method combining field surveys, remote sensing, modelled soil moisture anomalies and reports on crop conditions. The approach addressed a practical difficulty exposed by damaging droughts: assessments over large reporting areas could miss substantial local differences, while inspecting every cadastral area demanded considerable time. Their work estimated losses at cadastral scale and compared outcomes for the drought years 2017 and 2018. The reported assessment time fell from eight months in the first year to eight weeks in the second. The methodological advance joined environmental monitoring to an administrative problem, providing more timely evidence for decisions whose consequences were felt by individual farms.

Historical climatology supplied a different perspective on drought. In 2016, Rudolf Brázdil and an international group of collaborators reconstructed several drought indices for the Czech Lands back to 1501 by combining documentary and instrumental evidence. The indices described different aspects of water deficiency, allowing variability to be examined over centuries. The study identified particularly dry episodes around the beginning and end of the eighteenth century and the exceptional dryness of 1540. Such work placed contemporary observations within a longer record without assuming that every historical event could be measured as precisely as a recent one. It also demonstrated the continuing value of documentary scholarship in an increasingly computational research environment. Older evidence acquired new analytical uses through careful reconstruction and comparison.

The September 2024 flood tested the practical relationship between atmospheric prediction, hydrological knowledge and public action. The official assessment discussed in 2025 recorded the contribution of advance warnings and preparatory measures, alongside shortcomings requiring further work. During the event, the Czech Hydrometeorological Institute increased ALADIN calculations from four to eight runs a day for warning purposes. The assessment also considered communication between public authorities and the public. For a history of geographical science, the event shows how the effectiveness of forecasting depended on its passage into decisions about reservoirs, settlements and emergency preparation. Technical capability operated within an institutional and territorial setting. The interpretation of a forecast and the ability to act upon it were both relevant to the eventual consequences.

A further change became visible in October 2025, when the Institute began presenting fuller probabilistic hydrological forecasts on its flood information service. The product used seventeen possible developments generated from ALADIN-LAEF meteorological forecasts over the following sixty-six hours. Its graphs displayed a range of possible water levels and discharges, allowing users to consider the likelihood of dangerous thresholds being exceeded. A related presentation of predicted maxima responded to requests arising from the 2024 flood. The significance of this development concerned the communication of uncertainty as much as

the calculation itself. Users were offered a more explicit account of the spread of possible outcomes, helping them judge the urgency of action without concealing the limits of a forecast behind a single value.

Atmospheric research developed through complementary forms of observation. At the Košetice–Křešín site, the instruments associated with the atmospheric mast and the neighbouring observatory supported measurements of greenhouse gases, pollutants and aerosol properties. Equipment was moved into a new technical container at the mast in February 2016, and another container for aerosol research followed in summer 2017. Closer cooperation among the participating institutions led to the formation of the National Atmospheric Observatory Košetice in autumn 2017. These changes extended the scientific use of an installation that had entered service before the present period. They also brought together measurements with different purposes, allowing questions about atmospheric composition to be examined through a shared observational setting.

Aerology retained its own place within this expanding atmospheric science. The 2017 volume marking fifty years of the Praha-Libuš Observatory described the development of upper-air observation alongside radar and satellite meteorology, surface measurements and instrument calibration. Its account recorded the use of GPS-equipped RS92-SGP radiosondes at that time. Balloon soundings supplied vertical information about the atmosphere, complementing observations made at fixed heights or inferred remotely. This distinction matters when assessing the balance of Czech geographical sciences. Research on the free atmosphere was supported by a specialised observational practice with a history extending well before 1993. Its continuation within a changing technical environment illustrates how established measurement programmes could remain essential while other methods expanded around them.

Geodesy contributed to atmospheric research through the information carried by satellite signal delays. A 2016 paper led by Jan Douša, with collaborators including Michal Kačmařík and Radmila Brožková, described a benchmark campaign within the European COST Action ES1206. It compared tropospheric products derived from a dense GNSS network with parameters calculated from numerical weather models. The analysis examined delays and horizontal variations during a period containing severe precipitation events. For positioning, atmospheric delay is a quantity that must be modelled accurately; for meteorology, it can provide information about atmospheric conditions. The study demonstrated a productive relationship between these purposes and identified prospects for monitoring severe weather. It also made comparison between independently derived estimates central to assessing the quality of the proposed products.

The solid Earth sciences likewise combined improved observation with new forms of integration. The CzechGeo/EPOS-Sci project, conducted in 2017–2020, supported the modernisation of observatories and several research programmes. These included intraplate seismicity, participation in AlpArray research on the continental lithosphere, GNSS and gravity observations, and long-term monitoring of faults and slope deformation. A further programme concerned access to geological and geophysical data through modern information technologies. This combination connected questions about deep structure with

measurements of movement at the surface. The geographical extent of the work also exceeded the national territory, particularly in investigations involving the Alps and other European sites. Czech institutions contributed specialised observations to problems whose physical dimensions required cooperation across borders.

The European dimension acquired a more accessible digital form when EPOS presented its multidisciplinary data portal to the scientific community at the European Geosciences Union meeting in April 2023. The portal was intended to make different kinds of solid Earth data discoverable through a common environment. Within the Czech research setting, this development followed years of work on the integration of national observations. Its potential depended on the descriptions accompanying datasets and on the compatibility of the services through which they were supplied. Opening a portal did not complete the intellectual work of combining measurements. It provided a means through which researchers could locate material, assess its relevance and construct investigations using observations collected by institutions elsewhere.

Geological research also became involved in the practical assessment of responses to climate change. CO2-SPICER, undertaken in 2020–2024, prepared a pilot proposal for storing carbon dioxide in the mature Zar-3 oil and gas field in south-eastern Czechia. Coordinated by the Czech Geological Survey, the partnership included the Institute of Geophysics, VŠB–Technical University of Ostrava, MND and Norway's NORCE. Its tasks included a 3D geological model, simulations of injection scenarios, assessment of rock properties and risks, and a monitoring plan. These were preparatory investigations directed towards an implementation-ready project. They should be understood as evidence about the conditions under which storage might proceed, rather than as proof that a storage operation had already been established. The project brought subsurface interpretation into a contemporary debate about managing emissions.

Taken together, these environmental investigations reveal several meanings of methodological diversification. Some studies increased the detail of observation, whereas others extended its duration or brought different kinds of evidence into comparison. A drone survey and a reconstructed drought series addressed different questions, yet both depended on knowing how measurements from different times could be related. The common difficulty was to make change intelligible without confusing a difference in the record with a difference in the world. This concern also provided points of contact with human geography, where changing sources of information required researchers to reconsider the spatial and temporal units through which social processes were described.

Economic geography brought environmental change into its established analysis of production and regional dependence. Petr Pavlínek's study of the transition towards electric vehicle production, published online in 2022 and included in the 2023 volume of Empirica, examined eastern Europe as an integrated periphery of the European automotive industry. Combining industry statistics and other documentary material with earlier firm interviews in Czechia and Slovakia, the article considered how existing relationships constrained the emerging transition. It argued that foreign firms remained its principal drivers and that the pace differed from western Europe. For Czech economic geography, the contribution connected the industrial

transformation studied since the 1990s to a new technological and environmental setting. The location of factories remained relevant, but questions about decision-making power and the distribution of functions within production networks became equally important.

Social and regional geography acquired richer records of everyday movement. In 2021, Marián Halás, Vojtěch Blažek, Pavel Klapka and Stanislav Kraft published a study using mobile phone location data from across the Czech Republic. The work considered how to visualise flows between places while showing their direction and relative intensity. It also compared weekday and weekend movements and examined the transformation of flows through different interaction measures. This extended the evidence available for investigating settlement systems beyond conventional records of commuting to work or education. The resulting maps described relationships that changed with the rhythm of daily life. Their interpretation depended on understanding what the data recorded and how the processing of movements affected the geographical pattern presented to the reader.

The conceptual consequences became explicit in Halás's 2024 study of temporality in the delimitation of functional regions. Mobile phone data made it possible to distinguish regions based on regular daily movement, other daily flows and weekend activity. Several regional configurations could consequently be identified within the same national settlement system. The development involved more than improving the detail of an existing map. It questioned how far a region defined through one rhythm of movement could stand for the wider geography of people's lives. A boundary useful for investigating a labour market might have a different meaning when leisure or less regular journeys were considered. Regional geography was thereby revisiting one of its central concepts through evidence whose temporal detail earlier sources had rarely supplied.

The COVID-19 pandemic gave movement data a further practical significance. Work by Jan Platoš, Pavel Krömer, Miroslav Vozňák and Václav Snášel at VŠB–Technical University of Ostrava, published online in 2020 and in a 2021 journal issue, examined mobile network data and commuting during pandemic and non-pandemic conditions. This contribution came from computing and telecommunications, illustrating the broader disciplinary environment in which geographical analysis now developed. Aggregated records could help describe rapid changes that a periodic census would not capture at the same moment. Their use also required a distinction between investigating collective patterns and tracking identifiable individuals. The pandemic thus exposed both the analytical value of digital traces and the importance of the arrangements governing their production and use.

Participation offered a different way of expanding geographical evidence. Jiří Pánek's 2016 article on the movement from mental maps towards geoparticipation examined the changing role of residents in producing maps and informing decisions. Web applications and mobile devices allowed people without specialist GIS training to contribute spatial knowledge. The approach drew upon earlier work on perception and participatory mapping, giving those traditions a new technical setting. Its intellectual interest lay in recognising that residents could help determine which places and problems deserved attention. A map of perceived safety or valued public space contained evidence of experience that could not simply be inferred from

land-use categories. The method consequently widened the questions that geographical information systems could address.

By 2025, the accumulated material from such initiatives was itself becoming a subject of research. Pánek, Jakub Koníček and Jakub Žejdlík reported on eight years of participatory mapping in Ostrava, involving more than 8,000 respondents and over 70,000 spatial responses. Their work examined how the data could be organised and published through accessible web services. Consistent attributes and understandable visualisation were necessary if contributions made during different exercises were to remain useful. The case connects the social ambition of participation with the less visible work of maintaining data. It also raises a question for interpretation: the number of responses reveals the scale of engagement, while an assessment of whose experiences are represented requires attention to how participants were recruited and what they were asked to record.

Cartographic research increasingly examined how people understood the resulting representations. A 2025 study by Lukáš Herman and colleagues at Masaryk University compared photorealistic and symbolised 3D visualisations in a Brno planning experiment. Participants differed in their preferences and in their ability to complete tasks involving land use and change. Photorealistic scenes could be attractive and help some users understand a place, while symbolised models supported more accurate performance for some groups. These findings complicate any assumption that a more visually realistic model must communicate more effectively. For the development of Czech geography, the study shows digital cartography becoming a field of empirical enquiry into its own audiences. The usefulness of a representation could be tested against what readers actually understood and accomplished.

Political geography applied spatial methods to the changing electoral map. Jonáš Suchánek and Jiří Hasman's analysis of Freedom and Direct Democracy in the 2017 and 2021 parliamentary elections appeared online in 2022 and in its journal issue in 2024. The authors compared conventional regression with methods for examining spatial clustering and geographically varying relationships, including multiscale geographically weighted regression. This allowed them to investigate whether explanatory factors operated similarly across the country or at different spatial scales. The methodological choice reflected a substantive question about political change. National associations between electoral support and social characteristics could conceal regional differences in their relationships. Geography contributed an examination of context that could not be replaced by treating municipalities as interchangeable observations in a single national model.

Forced migration brought another set of urgent questions into social geography after Russia's full-scale invasion of Ukraine in 2022. A 2024 research report by Josef Novotný, Anna Levkova and Dušan Drbohlav, produced in cooperation with Slovo 21, examined Ukrainian refugees' circumstances and attitudes in Czechia. The research combined questionnaire surveys with six focus groups. Its initial survey included 1,037 respondents; later data collection continued into early 2024 and included renewed contact with 129 participants from the first round. This provided an opportunity to examine individual change alongside accounts of employment, language and possible return. The report explicitly discussed the limitations of its non-

representative samples. Its contribution illustrates the continuing importance of sustained contact with participants when geographical research addresses experiences that administrative totals cannot adequately explain.

The coexistence of these approaches makes a single account of digital modernisation insufficient. Movement records described interactions between places; focus groups helped researchers understand circumstances and judgements behind decisions. Spatial regression investigated variation in relationships, while participatory maps recorded selected experiences of the urban environment. Each method produced evidence at a different distance from the people or processes being studied. Methodological diversification therefore expanded the possibilities for comparison without making the resulting forms of knowledge interchangeable. For students and visiting researchers, the Czech experience offers a useful discipline of enquiry: begin with the question, examine what a source can reveal, and retain the contextual knowledge needed to understand its omissions.

By the end of 2025, Czech geography and the Earth sciences supported investigations that moved readily between observation sites, national datasets and international research systems. Their development can be traced through concrete changes in practice: repeated measurement of channel adjustment, spatially tested environmental predictions, the publication of uncertainty in flood forecasts, and closer analysis of the temporal structure of regional life. These achievements rested on earlier institutions and field traditions while placing new demands on calibration, interpretation and public communication. Environmental and societal change also gave the disciplines shared problems without dissolving their differences. Their strongest connections arose where researchers could bring distinct evidence into a reasoned account of how places were changing and why those changes mattered to the people living in them.

Part Two

The Czech Geography and Earth Science Research System

Universities, Academy Institutes and Public Research Organisations: Institutional Structure and Scientific Responsibilities

By the end of 2025, Czech geography and the Earth sciences formed a research system distributed across universities, Academy institutes and organisations with responsibilities for national scientific services. Its structure reflected the different kinds of work required to understand a territory. Teaching and the development of new research questions stood alongside the maintenance of observations, geological archives and geodetic reference systems. The same discipline could consequently have several institutional homes. Hydrology belonged to university departments, specialised research institutes and the national hydrometeorological service, each approaching water through a different combination of questions and obligations. These institutional relationships shaped both the evidence available to researchers and the routes through which scientific knowledge entered education and public decisions.

Public research organisations did not all share a single legal form. A public university had responsibilities for accredited education as well as research, while the designation veřejná výzkumná instituce, usually abbreviated to v. v. i., identified a particular form of public research institution. Academy institutes and several sectoral institutes operated within that framework. Other publicly funded scientific organisations had different arrangements: the Czech Hydrometeorological Institute, e.g., was a contributory organisation of the Ministry of the Environment. The Ministry of Education, Youth and Sports maintained the register of public research institutions. These distinctions mattered because the founder of an organisation, its governing bodies and its scientific partners did not necessarily perform the same role. Public funding connected the institutions to the state without making their functions identical.

Universities provided the most direct connection between research and the renewal of the scientific workforce. Under the Higher Education Act, university institutions could offer doctoral programmes and conduct research within a framework of academic freedoms and institutional autonomy. Faculties and departments gave that general responsibility a disciplinary form. Scientific boards and the university's academic bodies participated in the arrangements through which educational and research activity was organised and evaluated. For geography, the practical consequence was a continuing relationship between specialist enquiry and broader education. A department might sustain a focused research team while also teaching field methods, geographical theory and data analysis to students who would later work in schools, public administration or scientific institutes.

Charles University's Faculty of Science illustrates the breadth possible within a university geography section. Its 2024–2025 directory identified departments of Physical Geography and

Geoecology, Social Geography and Regional Development, Demography and Geodemography, and Applied Geoinformatics and Cartography. The structure placed natural and social approaches within a shared educational setting while retaining distinct methodological traditions. It also included supporting units such as the geography library, map collection and map and data centre. Their presence connected contemporary research with the preservation and interpretation of geographical records. The section's responsibilities thus extended from training researchers to maintaining materials through which earlier descriptions of territory could be revisited and compared with present conditions.

Geology at Charles University occupied a separate section of the same faculty. Its institutes covered geological and palaeontological enquiry, geochemistry and mineral resources, petrology and structural geology, and hydrogeology, engineering geology and applied geophysics. Shared laboratories supported analytical work across these specialisms. The arrangement shows why the administrative boundary of geography cannot serve as the boundary of this book's subject. Investigations of groundwater or slope stability could draw upon expertise organised under geology, even when the problem also concerned landscape processes studied by physical geographers. Keeping the units distinct allowed specialised training and equipment to be maintained; cooperation made those capabilities available to a wider scientific question.

Atmospheric physics had another university home in the Faculty of Mathematics and Physics. Its Department of Atmospheric Physics approached atmospheric phenomena through mathematical and physical description, including climate research, atmospheric chemistry and the dynamics of air movement. It also cooperated with Academy institutes and the Czech Hydrometeorological Institute. This placement was significant for the organisation of climatology. A climatologist working in a geography department might emphasise environmental differentiation or historical variability, while a physicist could examine the mechanisms represented in atmospheric models. The distinction concerned the organisation of expertise rather than an exclusive division of subject matter. Students and research projects could move between those perspectives through teaching and collaboration.

Masaryk University provided another substantial concentration of geographical and geological research. Within its Faculty of Science, geographical work included physical and human geography, geoinformatics, climatology and polar research. Geological research brought together analytical and field specialisms, while the Institute of Earth Physics maintained expertise in seismology and active tectonics, including earthquake monitoring. The university therefore combined several forms of scientific responsibility: educating geographers and geologists, maintaining specialist facilities, and sustaining field and observational programmes. Its polar work also reminds the reader that an institution's location did not delimit the territory of its investigations. Research organised in Brno could address environmental processes in distant settings while contributing to a common programme of university education.

At Palacký University Olomouc, the Faculty of Science distributed related work among geography, geoinformatics, geology, and development and environmental studies. Geography combined regional analysis with research on environmental and social questions.

Geoinformatics developed spatial modelling and cartographic approaches, alongside methods of collecting and communicating geographical information. Geological expertise supported research into rocks, sediments and contamination in the environment. This configuration gave the university several routes into problems that crossed disciplinary boundaries. A study of regional change might require spatial analysis and an understanding of development processes, while an environmental investigation could depend on geological evidence. The organisational distinction between departments allowed these contributions to remain recognisable within a collaborative investigation.

The University of Ostrava developed geographical enquiry through departments of Human Geography and Regional Development and of Physical Geography and Geoecology. The human geography department distinguished work on economic geography and regional development from political and cultural geography. Its subject matter included urban change and real estate, as well as nationalism, geopolitics and related political processes. The physical geography department combined teaching and fieldwork with facilities for sedimentological and geomorphological investigation. This institutional pairing supported an understanding of regional change through both environmental processes and social relationships. It also demonstrated that political geography had a clear university base within the Czech system, where it developed through identifiable teaching and research communities.

Ostrava's technical university, VŠB–Technical University of Ostrava, supplied a different concentration of expertise. Its Faculty of Mining and Geology connected mineral resources and their extraction with geological research, geoinformatics, mine surveying and engineering geodesy. Its research responsibilities included the environmental consequences of mining and the treatment of water and wastewater. Such work joined scientific investigation to the technical questions arising in landscapes altered by industrial activity. The university's role consequently differed from that of a general geography department, although their interests could meet in studies of environmental change and regional redevelopment. Its distinctive contribution lay in combining knowledge of the subsurface with methods for measuring and managing the effects of its use.

Geodesy and geomatics also depended on technical university traditions elsewhere. At the Czech Technical University in Prague, the Faculty of Civil Engineering's Department of Geomatics combined education with research in cartography, photogrammetry, remote sensing, mapping and spatial information systems. At the University of West Bohemia in Pilsen, geomatics research addressed geodata acquisition and modelling, including applications to the Earth's gravity field and spatial planning. These centres placed geographical measurement alongside engineering and computation. They provided a route into the Earth sciences for researchers whose principal training concerned the accuracy and organisation of spatial information. Their work also supplied methods used by colleagues investigating landscapes, infrastructure and environmental processes.

Agricultural and environmental faculties widened the system further. Mendel University in Brno's Department of Agrosystems and Bioclimatology connected long-term field experiments with the study of climate impacts and adaptation in agricultural systems. At the Czech University of Life Sciences Prague, hydrological and climate research within the Faculty of

Environmental Sciences combined observations, numerical modelling and experimental catchment work. These settings gave climatology and hydrology a practical connection to land management. They also brought different forms of training into environmental research, including agricultural science and engineering. The institutional picture therefore extended beyond departments carrying geography or geology in their names, particularly where the object of investigation was a managed landscape.

Regional university departments performed important functions through the combination of research, teacher education and public engagement. The University of South Bohemia's geography department, located in its Faculty of Education, combined physical and human geographical topics with education for teaching and public administration. Its scientific interests included geomorphology, transport, migration and urban geography, and it worked with schools and organisations concerned with regional development. Its contribution included maintaining geographical expertise within a region and ensuring that research informed the education of future teachers and practitioners. This was one of the routes through which geographical knowledge reached audiences beyond the research community.

Across the universities, the working unit of research was often smaller than the faculty or department named in an organisational chart. A specialist group could bring together staff and doctoral students around a catchment, a form of spatial analysis or a question about regional change. Its collaborators might belong to another faculty or to an external institute. The department remained important for employment, teaching and the continuity of a discipline, but the scientific relationships followed the requirements of the investigation. For an international researcher, this distinction is useful: the formal host identifies an institutional setting, while the research group reveals the methods, evidence and intellectual discussion through which a project is actually conducted.

The Czech Academy of Sciences (CAS) supplied another framework for sustaining specialist research. Its statutes described a system of autonomous institutes with responsibilities for scientific enquiry, the dissemination and use of results, and cooperation with universities. The transformation of its institutes into public research institutions took effect in January 2007 and strengthened their legal personality. Institute leadership and governing boards operated within an organisation founded by the Academy, while scientific relationships extended beyond it. The consequence was a form of continuity different from the regular cycle of university degree programmes. Specialist teams could maintain analytical capabilities and observational commitments while contributing to teaching through cooperative arrangements with higher education institutions.

The Institute of Geophysics illustrates the close relationship between research and national scientific service within this framework. Its work encompassed the Earth's physical structure and processes, using theoretical approaches alongside modelling and field observations. It also maintained observations of physical fields, including seismic, geomagnetic, geodynamic and geothermal phenomena, and exchanged data with international networks. These activities gave the institute responsibilities extending beyond the production of individual papers. An observational record acquired scientific value through continuity and through its relationship to measurements elsewhere. Researchers also taught and supervised students at universities,

allowing this specialised environment to contribute to the preparation of new scientists without requiring the institute to duplicate the full educational responsibilities of a university.

The Academy's Institute of Geology maintained a different body of expertise. Its research structure brought together geological processes, palaeobiology and palaeoecology, environmental geology and geochemistry, analytical methods and palaeomagnetism. Field material and laboratory interpretation supported investigations across different periods of Earth history. Its institutional presentation also emphasised cooperation with universities and access to capabilities held by other organisations. The institute should be distinguished from the Czech Geological Survey. The former was an Academy research institution with its own scientific programme; the latter combined research with the national geological service. Their interests could overlap closely, but their responsibilities gave different purposes to the maintenance of expertise and the production of geological information.

The Institute of Rock Structure and Mechanics occupied a position connecting geological knowledge with the behaviour and properties of rock materials. Its remit included engineering geological and related investigations, alongside research on materials with technological applications. Its declared responsibilities also covered the operation of research infrastructure and cooperation in doctoral and postdoctoral preparation. In the wider system, this combination supported investigations in which a geological setting had to be understood through its mechanical behaviour and possible instability. The relevant expertise could contribute to natural hazard research while also serving engineering questions. This was another instance in which the boundaries of the Earth sciences were shaped by the problem under investigation as well as by disciplinary convention.

The Institute of Geonics connected research on human interventions in the Earth's crust with their environmental and social consequences. Alongside geomechanical and technical work, it maintained environmental and social geographical expertise. Its Department of Environmental Geography studied interactions between society and natural and political environments, including urban transformation, energy-related land-use conflicts and changes in agriculture. Within the Academy, the department gave human geography an institutional base alongside expertise in engineering and physical processes. Research on the social acceptance of energy projects, for instance, could connect the physical characteristics of landscapes with the decisions through which they were used. Such questions required methods capable of examining social relationships as well as environmental conditions.

The Institute of Atmospheric Physics supported research on atmospheric processes through departments concerned with meteorology, climatology and other aspects of the atmosphere and near-Earth environment. Meteorological work included the operation of the Milešovka and Kopisty observatories. Climatological enquiry addressed variability and change, extremes in climate models, and relationships between atmospheric circulation and surface conditions. Its responsibilities therefore combined specialised observation with the examination of physical mechanisms. This role complemented the university preparation of atmospheric scientists and the operational responsibilities of the hydrometeorological service. The institutions could study related phenomena while requiring different outputs from their work, ranging from the testing of an explanation to the provision of an observation or forecast.

Water research within the Academy was conducted at the Institute of Hydrodynamics, the name in force through the end of 2025. Its scientific development had brought hydrology and water treatment increasingly to the centre of its programme. Following restructuring, departments of Hydrology and of Hydrochemistry and Water Technology were established in July 2022. The arrangement connected understanding of water movement with the processes affecting water quality and treatment. Its established name consequently described only part of an evolving research programme. Within the period examined here, the institute's contribution increasingly concerned water as an environmental resource whose behaviour and quality required closely related scientific approaches.

CzechGlobe, the Global Change Research Institute, extended the Academy's environmental research across the atmosphere, ecosystems and society. Its core purpose was to produce new knowledge about global change, including exchanges of energy and substances and the consequences of climatic change. It also sought to make results useful to public bodies and other users. This combination placed a basic research institute in continuing contact with practical questions about adaptation and mitigation. Those connections brought geographers, atmospheric scientists and researchers trained in other environmental fields into common investigations. These investigations examined how changes in atmospheric conditions and ecosystem processes interacted with human activity.

The Czech Hydrometeorological Institute had a more explicitly operational national responsibility. As an organisation of the Ministry of the Environment, it maintained monitoring and observation networks, processed and archived records, and supplied information, forecasts and warnings. Its remit brought together meteorology and climatology, hydrology and air quality, supported by regional branches. Research and technological development were part of this activity, helping to improve the methods on which public services depended. The distinction from a university laboratory was consequential. An experimental project could concentrate on a particular event or process, while the national service had to sustain observations and provide information when users needed it. That continuing responsibility also generated records essential to research undertaken elsewhere.

Aerology provides a particularly clear example of how responsibilities were distributed. Balloon soundings at Praha-Libuš belonged to the observational work of the hydrometeorological service, while university atmospheric physics and Academy research supplied related analytical and theoretical expertise. The observatory's 2017 institutional history placed upper-air measurement alongside radar, satellite and surface observation and the calibration of instruments. Aerology was thus supported through a combination of observation and research settings rather than through a separate institution bearing that disciplinary name. Identifying the practice and its custodians is more informative than looking for an aerology faculty. It also prevents the organisational dispersal of a field from being mistaken for an absence of scientific activity.

The Czech Geological Survey fulfilled a national role in the production and preservation of geoscientific information. Geological mapping, research on mineral resources and groundwater, assessment of geohazards and the management of geological records were connected to its state geological service. The Survey's purpose included providing information

for decisions about resources, hazards and sustainable development. Its responsibility for a national body of information gave research an enduring territorial setting. A map or geological model could draw upon observations collected over many years, while the interpretation might be revised as new evidence became available. Universities and Academy institutes could contribute to this work without assuming the Survey's wider obligation to organise and maintain information for national use.

The T. G. Masaryk Water Research Institute, a public research institution founded by the Ministry of the Environment, connected water science with management and environmental protection. Its work combined hydrological and hydrogeological enquiry with water quality, ecological assessment, laboratory methods and information services. With workplaces in Prague, Brno and Ostrava, it also provided a regional presence for specialised investigation and expert support. Its 2025 institutional publication described work ranging from drought assessment and groundwater replenishment to water-quality monitoring and laboratory services. This combination distinguished it from the flood forecasting service even where both institutions dealt with water extremes. Its scientific responsibilities extended to the methods and evidence needed to assess the condition, use and protection of water resources.

Landscape research had a further institutional base in the organisation formerly known as the Silva Tarouca Research Institute for Landscape and Ornamental Gardening. On 1 January 2025 it adopted the Czech name Výzkumný ústav pro krajinu, abbreviated to VÚK. The institute's announcement explained the change through the breadth of its work on landscapes, environmental risks and biodiversity, and its provision of independent expert support to public administration. Existing departmental activities continued. The change is relevant to the structure of geographical research because it made the wider landscape remit more explicit. It also demonstrates why institutional history requires attention to continuity beneath a new name: a renamed organisation could retain its teams and projects while clarifying the public purpose of their work.

The Research Institute of Geodesy, Topography and Cartography, known as VÚGTK, provided specialised research for geodetic and cadastral applications. Its mission included geodesy and geodynamics, metrology, cartography, photogrammetry and the development of methods and software. The Geodetic Observatory Pecný formed part of its scientific setting. Registered as a public research institution from 2007, with the Czech Office for Surveying, Mapping and Cadastre as founder, the institute connected analytical research with the reliability of measurement and spatial records. This connection mattered throughout the wider Earth sciences. Observations could be compared meaningfully only when researchers understood the reference systems, instruments and processing through which positions and movements had been determined.

Within the same public surveying system, operational responsibilities belonged to bodies such as the Land Survey Office. It administered and operated CZEPOS as part of the national geodetic foundations, supplying correction data for precise satellite positioning. This role should be distinguished from VÚGTK's research mission and from the educational responsibilities of technical universities. The organisations were connected through the need for reliable spatial measurement, yet their outputs served different purposes. A researcher

developing a method, a university preparing a surveyor and an office sustaining a national positioning service contributed to the same capability through different institutional commitments. Their relationship helps explain how geodesy supported the rest of the research system without being concentrated in a single organisation.

Shared infrastructures gave these distributed capabilities a more organised form. CzechGeo/EPOS brought together observations maintained by Academy institutes, universities and other geoscientific organisations. Permanent networks were complemented by local and mobile stations, allowing different observational arrangements to serve related investigations. The institutional significance concerned coordination between organisations that retained their own responsibilities. Participation created a route through which a university team could work with records or facilities maintained elsewhere, while observational institutions could contribute to a wider programme of enquiry. The consortium therefore added a common scientific structure across existing organisations rather than requiring all relevant researchers and instruments to belong to one institute.

CzeCOS offered another arrangement, with CzechGlobe hosting facilities that external researchers could seek to use through scientific projects. Its access procedures considered scientific merit and technical feasibility. The distinction between the host of an infrastructure and its scientific users was therefore built into its operation. For a researcher, institutional affiliation alone did not describe the full environment in which an investigation could be conducted. A project might be based at a university and depend on an experimental or observational facility maintained by an Academy institute. Such arrangements widened the usable research system while preserving responsibility for the operation and maintenance of specialised equipment.

Doctoral preparation was one of the most important connections between these institutional settings. Universities supplied the accredited programme and awarded the qualification, while researchers at Academy and sectoral institutes could contribute supervision, teaching and access to specialised work. The Academy's statutes expressly recognised cooperation with universities in doctoral programmes. This relationship allowed a student's scientific training to extend beyond the facilities of the awarding institution. It also placed an obligation on the partners to connect specialist participation with a coherent educational programme. The value of access to an observatory or laboratory depended on the intellectual guidance through which the student learnt to frame a question and interpret the resulting evidence.

Scientific responsibility also included the continuing care of the materials from which research could be made. Geological collections and archives, map holdings and long observation series required decisions about description, preservation and access. These tasks were often less visible than a newly published result, yet they allowed findings to be checked and earlier observations to acquire new uses. Across the institutions considered here, the maintenance of such resources formed part of the practical relationship between scientific continuity and innovation. A research system could develop new methods more effectively when the records to which they were applied retained an intelligible history.

The resulting institutional structure combined several forms of accountability. Universities answered for the quality of education and research, specialist institutes for their scientific programmes and facilities, and national services for observations and information supplied in the public interest. Their cooperation worked best when those responsibilities were understood clearly. For participants in international research and training, the appropriate point of entry was consequently defined by the question being pursued and the evidence required. Czech geography and the Earth sciences offered a network of possible partners whose capabilities overlapped without becoming interchangeable. Its strength lay in the relationships through which specialised knowledge could be sustained, taught and brought to bear on problems extending beyond the boundaries of any one institution.

National Scientific Services: Geological, Hydrometeorological and Geodetic Research and Observation

National scientific services gave Czech geography and the Earth sciences a continuing supply of evidence whose collection could not depend on the duration of an individual research project. Geological maps, river records and geodetic reference points acquired their value through repeated use, careful revision and a documented history. Between 1993 and 2025, the organisations responsible for these resources combined public duties with research that altered how observations were made and interpreted. Their development helps to explain why scientific innovation sometimes appeared as a better forecast or a more dependable coordinate transformation, rather than as a new academic specialism. It also reveals the considerable work required to turn a measurement taken in one place into information that could be trusted elsewhere.

The establishment of the Czech Republic in 1993 changed the state within which these services operated, while leaving much of their professional inheritance intact. Existing staff, instruments and collections supplied the means of continuing national observation. Subsequent changes concerned institutional responsibilities, computing and the terms on which information circulated. The Czech Geological Survey, the Czech Hydrometeorological Institute and the organisations within the surveying and cadastral sector followed different paths. They shared, however, a practical obligation to provide evidence for decisions beyond the research community. Their histories consequently have to be read through the relationship between scientific enquiry and the regular provision of a public service.

At the beginning of the period, the principal geological organisation bore the name Czech Geological Institute, adopted in 1990. Its renaming as the Czech Geological Survey in 2002 made the national service function more explicit. A further change brought the geological research and mapping organisation together with CGS–Geofond, which had maintained a separate responsibility for geological information and documentation. Geofond ceased to exist as a separate state organisational unit on 31 December 2011; the Survey’s annual report described 2012 as the first year of the reunited service. This reorganisation placed the

acquisition of new geological knowledge and the preservation of earlier investigations within a common institution. The same report recorded financial pressure and staff reductions, reminding the reader that institutional consolidation also involved difficult choices over capacity.

Geological mapping remained a research activity because the content of a map depended on interpretations that could be reconsidered. Field observations had to be reconciled with laboratory evidence and the findings of earlier surveys. From 1999, the GEOČR25 programme developed detailed regional mapping at 1:25,000, while GEOČR50 provided a geological database covering the whole country at 1:50,000. The associated information systems connected geological observations with hydrogeological and environmental material. Mapping therefore supplied a common geographical framework within which specialists could examine relationships between bedrock, superficial deposits and water. A completed national map series did not bring this investigation to an end. It established a reference against which more detailed work and revised explanations could be assessed.

The Survey's documentary responsibilities extended that framework beneath the surface. Borehole descriptions, drill cores and unpublished reports preserved observations from places that might be inaccessible to a later researcher. Written records and physical specimens had different evidential qualities: an older description recorded an interpretation, whereas a surviving core could sometimes be examined with methods unavailable when it was recovered. By maintaining both forms of documentation, the service made it possible to return to earlier geological questions without repeating every expensive field operation. Digital catalogues improved discovery, although a catalogue entry could not convey everything that a report or sample contained. The scientific usefulness of an archive still depended on identifying the provenance and limitations of its materials.

Slope instability brought these responsibilities into direct contact with geomorphology and public protection. The Survey dates its systematic mapping of slope deformations to 1997. Field investigation, the documentation of individual movements and the incorporation of records into geographical databases allowed observations made after damaging events to contribute to a broader understanding of susceptible terrain. Such information could inform land-use planning and the examination of particular sites. Its interpretation required care: an inventory of recorded movements described where evidence had been found, and its completeness depended partly on the history of investigation. The RENS research programme, under way from 2020, explicitly connected newer field information with historical records. This work illustrates how a national service could improve the evidence available for geological hazard assessment while maintaining continuity with earlier surveys.

Mineral information formed another enduring connection between geology and the public affairs of the country. The Survey's Mineral Commodity Summaries brought together information on production, resources and reserves, together with prices and foreign trade. The 2025 edition reported data through 2024, a distinction that matters when tracing developments over time. These publications provided material for examining the geographical consequences of extraction and changing demand. Geological occurrence, the classification of a resource and the conditions under which material could be extracted profitably nevertheless remained

different questions. For economic geographers, the service offered an empirical basis for investigating those relationships. Its information could support an argument about regional development or resource dependence without itself constituting a complete explanation of either.

Hydrogeology showed especially clearly how the responsibilities of national services could meet. During 2010–2016, the Survey led Rebilance zásob podzemních vod, a reassessment of groundwater resources in 58 hydrogeological regions. The project evaluated long-term natural resources for the reference period 1981–2010 and combined geological investigation with hydrological and groundwater-flow modelling. It concentrated on regions where groundwater had particular importance for water supply. More than a hundred monitoring boreholes were drilled, with their subsequent inclusion in the state groundwater observation network operated by the Czech Hydrometeorological Institute envisaged as a continuing process. The project thus linked a bounded investigation with a longer observational responsibility. Geological knowledge helped to define the aquifer being studied, while continuing measurements could test how its behaviour varied after the project had ended.

The GEOMON network gave geological research a further connection with environmental change. Established in 1994, this monitoring of small forested catchments investigated the movement of water and chemical substances through landscapes. The Survey's account of its work in 2014 placed GEOMON alongside the longer observation of glacial lakes in Šumava in research on terrestrial and aquatic ecosystems. Catchments were useful units because atmospheric inputs could be considered together with the chemical composition of drainage water and the properties of soils and bedrock. A change in stream chemistry could then be examined as a response involving several processes. The value of the network lay partly in retaining observations across changing environmental conditions, allowing hypotheses about recovery or disturbance to be assessed over a longer period than a single campaign could provide.

European cooperation changed the organisation of geological information as well as the geographical extent of research. In OneGeology-Europe, launched in 2008, the Czech Survey was responsible for a multilingual metadata catalogue. In 2016 it became one of the founding participants in the European Geological Data Infrastructure, the EuroGeoSurveys information platform. These developments addressed a practical difficulty in comparative science: neighbouring maps could use different classifications and descriptive conventions. Making them visible through the same system was only the beginning. Researchers also needed to understand whether apparently similar units or attributes had the same meaning. The Czech contribution to metadata and shared infrastructure therefore belonged to the scientific work of comparison, helping users to judge what could reasonably be combined across national boundaries.

The Czech Hydrometeorological Institute entered 1993 with an established national identity: Czech and Slovak hydrometeorological institutes had already been organised separately within the federation in 1969. Its later development joined improvements in observation to changes in forecasting arrangements. New weather radars entered service at Skalky in Moravia in 1996 and at the summit of Praha in the Brdy Mountains in 2000. A Central Forecasting Office

was established in 1999. These changes strengthened the means of following weather systems across the country and relating regional evidence to national forecasts. They also made the Institute an important source for researchers whose questions required spatially extensive observations rather than measurements from a single experimental site.

Automation altered the daily practice of observation during the same period. Pavel Lipina, Radim Tolasz and Dušan Židek's account of the Ostrava branch's automated station network, published in 2000, treated the construction of the network together with its operation and relationship to climatological databases. This was a useful conception of innovation. Installing an automatic instrument changed how information reached the service, but the resulting record still required checking and a connection with earlier observations. Where equipment or procedures changed, the interpretation of differences through time became a scientific concern. Automation increased the amount and timeliness of available information while making the description of the observing system an essential part of its use.

The development of CLIDATA addressed this problem from the side of data management. In his 1998 discussion of new directions in climatological databases, Tolasz described work towards a relational system intended to replace CLICOM. The proposals connected developments within the Czech service with discussions under the World Meteorological Organization. Database design affected the questions that could be answered efficiently: observations had to remain associated with the stations and circumstances from which they came, and quality control had to be possible across large collections of records. The history of Czech climatology therefore included work on the organisation of information as well as on atmospheric processes. A database could preserve earlier measurements while enabling them to be examined in combinations that had previously been laborious to assemble.

The Climate Atlas of Czechia, published in 2007 under Tolasz's editorship, demonstrated what sustained observational work could support. Its more than three hundred maps, accompanied by explanatory material in Czech and English, presented a spatial synthesis based largely on 1961–2000. Preparing the atlas involved checking data, reconstructing series and developing methods of geographical analysis. The resulting publication connected the observing service with university expertise and cartographic research. It also made clear that national climatological information was an interpreted product. A reader encountered the outcome of decisions about periods, the treatment of incomplete records and the representation of variation across terrain, rather than an unmediated collection of station readings.

Aerology remained a substantial component of this observational system. The Institute's report for 2024 recorded one aerological station, two sodars and four wind profilers, alongside its weather radars and surface networks. These categories described different ways of observing the vertical structure of the atmosphere. Balloon-borne soundings at Praha-Libuš supplied profiles of atmospheric conditions, while remote sensing offered complementary information about winds and the lower atmosphere. Such evidence mattered because conditions at the ground could not adequately describe the air above it. Stability and vertical wind structure affected the interpretation of weather development and pollutant dispersion. Czech aerology consequently had a continuing operational and scientific role, even though it

was usually housed within meteorological organisations rather than presented as a separate institutional discipline.

Numerical prediction provided another meeting point between scientific research and routine service. The ALADIN programme developed through cooperation with Météo-France and the central European RC LACE partnership. In 1998 the ALADIN-LACE application moved from Toulouse to the Czech Institute in Prague, giving the Czech service a responsibility within a shared forecasting system. A later operational change, introduced in March 2019, increased horizontal resolution from 4.711 to 2.325 kilometres and adopted a non-hydrostatic dynamical core. The change required both research on the representation of atmospheric processes and sufficient computing capacity to complete forecasts on time. Operational forecasting thus imposed a demanding test on innovation: a scientifically promising method also had to work reliably within a daily schedule.

Hydrological observation required a similarly close relationship between measurement and interpretation. The Institute’s Hydrological Yearbook for 2024 brought together assessments of surface water and groundwater, hydrological balances and water quality. Snow observations also contributed to understanding water stored temporarily in catchments. These records supported comparisons between a particular year and longer-term conditions, while preserving regional differences that a national average could conceal. For research, the value lay in the possibility of examining several parts of the water cycle together. A decline in streamflow could be considered alongside groundwater levels and preceding climatic conditions. The yearbook also provided a settled assessment against which the more immediate information issued during an unfolding event could subsequently be understood.

The history of flood forecasting showed why services repeatedly revised their working arrangements. The professional guidance edited by Jan Kubát, Radek Čekal, Jan Daňhelka and Václav Matoušek in 2012 described the revision of the flood reporting system after the 1997 disaster and further amendments following subsequent major floods and legislative changes. Its treatment of reporting profiles and the organisation of flood protection connected hydrological expertise with those responsible for responding locally. A forecast had practical value when it reached the appropriate people in a usable form and with sufficient time to act. The development of the service therefore involved communication and agreed procedures alongside improvements in models. Experience of damaging events exposed weaknesses that purely technical evaluations might leave unnoticed.

By the end of the period, the public presentation of uncertainty had become more explicit. From the middle of October 2025, the Institute’s flood forecasting website displayed probabilistic hydrological forecasts based on seventeen variants driven by ALADIN-LAEF meteorological predictions over 66 hours. The accompanying explanation taught users to read ranges of possible water levels and discharges. A table of predicted maxima also responded to requests made after the September 2024 flood. This development brought scientific uncertainty into the public service itself. It required users to consider the likelihood of dangerous conditions and their possible timing, rather than treating one forecast trajectory as an assured description of the future.

Air-quality assessment gave the Institute a further responsibility relevant to geographical research. Its assessment of 2024 examined pollutant concentrations over space and time, using observations together with modelling. The explanation of relatively favourable conditions considered both emissions and the influence of weather on heating demand and dispersion. Ground-level ozone did not follow the same declining pattern as most other pollutants over 2014–2024. Such differences demonstrated the need to distinguish substances and processes when interpreting environmental improvement. For social and economic geography, these assessments could help locate unequal exposure and examine connections with settlement or industrial activity. The public dataset supplied evidence for those investigations; explaining the social distribution of exposure required additional geographical analysis.

The relationship between observation and public responsibility acquired a clearer legal expression at the end of the study period. Act No. 262/2024 Coll., effective from 1 January 2025, defined the public hydrometeorological service and retained the Institute as a state contributory organisation under the Ministry of the Environment. It explicitly included scientific, research and educational activities among its main tasks, while also recognising the Ministry of Defence's responsibilities for hydrometeorological service within its remit. The Act provided for a national database and the remote public availability of its contents as open data, subject to its provisions. It distinguished observations from data that had undergone quality control and from processed products. This vocabulary recognised a scientific sequence that mattered to users: information changed its evidential status as it was checked and interpreted.

Applied water research extended the system beyond the Institute's observation and forecasting duties. The T. G. Masaryk Water Research Institute's 2025 account described the HAMR drought system, laboratory investigations and a calibration station at Prague-Podbaba. A particularly concrete example followed the Bečva pollution disaster: pilot monitoring began in January 2021, and automatic monitoring using living water fleas was formally launched in June 2022. Here, research concerned the detection and interpretation of water-quality deterioration. The calibration of flow-measuring equipment addressed a different but related requirement, the reliability of the measurements themselves. These activities complemented national hydrological observation and showed how specialised research could develop methods that subsequently supported environmental monitoring and water management.

Geodetic services supplied a different kind of continuity. Their task was to maintain a dependable spatial reference within which measurements from different surveys could be related. In the Czech system, the Czech Office for Surveying, Mapping and Cadastre provided the central administrative framework, while the Land Survey Office maintained national geodetic foundations and mapping resources. The Research Institute of Geodesy, Topography and Cartography, generally known by its Czech abbreviation VÚGTK, developed methods and technologies relevant to these duties. This allocation mattered because a research result, a national reference network and a cadastral record carried different responsibilities. The scientific development of geodesy had to be connected with the practical stability needed by surveyors and other users of spatial information.

The early post-1993 work on reference systems illustrates the care this connection required. The CS-BRD campaign in 1993 linked Czech and German GPS networks, while DOPNUL in

1993–1994 extended the European reference framework through points with coordinates in both ETRS89 and the established Czech S-JTSK system. A later report by Jan Douša and colleagues on the EUREF-Czech-2009 campaign reviewed this inheritance and the need for a more consistent realisation. The underlying problem was partly historical: the national surveying system and satellite-based reference systems had been established through different methods and at different times. Their relationship had to be measured and modelled. European integration in geodesy consequently involved the detailed reconciliation of spatial references, with direct consequences for the acceptance and reuse of survey results.

At the Geodetic Observatory Pecný, maintained within VÚGTK, observations connected Czech research to international scientific services. The observatory combined satellite geodesy with gravimetry and environmental measurements. Its work included GNSS data collection and analysis, contributions to the International GNSS Service and the European reference network, and observations relevant to the Earth's gravity field. Housing several techniques at one site allowed researchers to examine relationships between measurements and their surroundings. Apparent changes in position or gravity required explanation through instrument behaviour, reference conventions and physical processes. The observatory's responsibilities for archiving and disseminating data were therefore closely connected with its research: other investigators needed access to records whose origin and processing could be understood.

The establishment of CZEPOS widened access to precise positioning. Its first stations were installed in 2004; the official chronology records post-processing data services from March 2005 and real-time services from June that year. Full operation followed on 1 January 2007, after the testing period. The Land Survey Office administered the network as part of the national geodetic foundations. Permanent stations supplied observations and corrections that surveyors could use without establishing all reference measurements independently for each job. The research significance extended beyond convenience. A continuing network created records against which the stability of positions and the behaviour of measurement systems could be examined, provided that changes in receivers, antennas and processing were documented.

Later development involved the scientific verification of the service as well as the reception of more satellite signals. The receiver and antenna upgrade completed in May 2012 supported GPS and GLONASS while preparing for Galileo. In October 2019, new network solutions incorporated GPS, GLONASS, Galileo and BeiDou corrections; further services followed in 2020 and 2021. The chronology records successive changes in data formats and access arrangements rather than a single completed conversion to satellite geodesy. By 2024, the sectoral report described a network incorporating stations in neighbouring countries as well as those within Czech territory. National positioning services had become dependent on continuing technical cooperation across borders, even while responsibility for the Czech service remained clearly assigned.

VÚGTK's contribution included independent monitoring of reference stations and research on precise data processing. Its metrological work also supported the maintenance of standards and the calibration of instruments used in surveying and related professions. The sector's report for 2024 described research on changes in gravitational acceleration, national

standards and the stability of GNSS reference positions. These activities supplied a means of distinguishing a change in the environment from a change introduced by measurement. That distinction could become consequential when a small displacement was interpreted as evidence of ground movement. Scientific responsibility therefore extended to assessing the conditions under which a result could be reproduced, rather than merely reporting the number of decimal places produced by an instrument.

Satellite geodesy also created opportunities for atmospheric research. Signals passing through the atmosphere experienced delays that had to be estimated for precise positioning, but those estimates could themselves contain meteorological information. A 2016 study led by Douša, involving Czech and other European institutions, assembled a central European benchmark dataset and compared GNSS tropospheric products with numerical weather models. It examined delays and horizontal gradients during a period that included heavy precipitation and flooding. This work made the connection between geodetic and hydrometeorological services scientifically productive. Measurements developed for locating a receiver could also help investigate atmospheric moisture, provided that the relevant signal components were modelled and independently assessed.

National elevation data offered another connection with physical geography. Following preparatory work in 2008–2009, airborne laser scanning during 2010–2013 supplied observations for new digital terrain products. The fifth-generation terrain model, DMR 5G, achieved national coverage in June 2016. This was a joint undertaking involving civilian and military surveying expertise. The distinction between observation dates and completion of a processed model is essential when using these products historically. Terrain data gave geomorphologists and hydrologists a more detailed basis for examining relief and drainage, although the model represented a surface derived from observations and processing decisions. Its application required attention to vegetation, classification and the date represented. Later surveys could be compared with it only after the investigator had established that differences reflected comparable surfaces and consistent spatial references.

The expansion of open data changed who could make such investigations. From 1 July 2023, the range of Land Survey Office products supplied as open data widened to include major topographic and elevation datasets, orthophotography, geographical names and geodetic point information. The 2024 reporting described access through the national geoportal, with metadata accompanying downloadable files. This reduced the practical barrier to using authoritative national information in research and teaching, including international work undertaken at a distance. Access alone did not settle questions of fitness for purpose. Users still needed to examine resolution, acquisition history and coordinate conventions, especially when combining terrain models with geological information or hydrometeorological observations collected on a different basis.

Across 1993–2025, these services supported geographical disciplines in unequal but complementary ways. Geology, climatology and geodesy were directly represented in their scientific duties; geomorphology and hydrology drew on several overlapping services. Economic, social and political geographers usually approached them as sources of evidence about resources, environmental conditions and the organisation of territory. The services’

public status also made their own decisions legitimate subjects of geographical enquiry. What was observed, how information was classified and where expert assessment entered public decision-making could influence which regional problems became visible. Understanding these institutions therefore helped researchers evaluate both the environmental records they used and the circumstances under which those records had been produced.

The most consequential changes of the period often lay in relationships between activities that had once been harder to connect. Geological documentation became more closely integrated with research and mapping. Automated observations entered databases from which new syntheses could be prepared. Permanent satellite networks linked field measurement with international reference systems, while open-data provision widened the community able to work with national evidence. Each development increased the need to preserve a clear account of methods and revisions. A researcher comparing Czech observations with material from another country consequently needed to examine the history of both records. The services' documentation of instruments, classifications and processing methods made that comparison more defensible and gave continuing public observation a scientific value beyond its immediate administrative purpose.

Regional Research Centres, Scientific Schools and the Spatial Organisation of Czech Science

The development of Czech geography and the Earth sciences between 1993 and 2025 had a distinct spatial pattern. Prague retained a large concentration of institutions and researchers, while Brno sustained several influential research traditions. Other university cities developed specialisms whose significance exceeded the size of their departments. Across this system, scientific work depended on relationships between people and places: a laboratory might serve several organisations, a research group might investigate a distant landscape, and a doctoral student might carry an approach from one centre to another. Regional development in science therefore involved both the concentration of resources and the circulation of expertise. Understanding those relationships explains more than a catalogue of institutional addresses can convey.

A scientific school becomes recognisable through the persistence of questions and methods across successive groups of researchers. Its members acquire ways of selecting evidence, testing explanations and training students, while retaining the capacity to revise their predecessors' assumptions. A research centre has a more readily identifiable institutional or geographical form, although it may contain several such traditions. During the period considered here, the relationship between the two changed. Established programmes survived institutional reorganisation, and newer laboratories acquired coherent research agendas through shared instruments and sustained collaboration. The relevant historical evidence consequently includes publications and supervision as well as the founding dates of departments.

The wider distribution of Czech research provided an unequal setting for this development. Official statistics for 2024 allocated approximately 41% of national research and development expenditure to Prague, 17% to South Moravia and 13% to Central Bohemia. These figures cover research and development across all fields, including business activity, and cannot establish a ranking of geographical or Earth science departments. They do, however, indicate the concentration of the broader scientific environment within which those departments worked. Administrative boundaries also complicate interpretation: a centre located in Central Bohemia could form part of a research network organised around Prague. The geographical distribution of expertise was more intricate than the distribution of expenditure alone suggested.

The reorganisation of Academy geography in 1993 offers an early example of how that distribution could change without eliminating an existing tradition. Following the dissolution of the former Geographical Institute, an environmental geography centre was established in Brno within the Institute of Geonics. Its institutional home was an Academy institute headquartered in Ostrava, while its geographical research remained based in Brno. This arrangement preserved a regional concentration of expertise within a reorganised national structure. Over subsequent years, its work developed around interactions between environmental and social processes, including landscape change and the transformation of settlements. The history resists any simple equation between the disappearance of an institutional name and the disappearance of the research that had been conducted under it.

Prague's contribution rested partly on the continuing influence of theoretical work in social geography at Charles University. Martin Hampl's investigations of geographical organisation, settlement hierarchies and regional differentiation provided concepts through which the changes after 1989 could be examined. Their influence extended through teaching and discussions with younger colleagues. The account published by Hampl and Miroslav Marada in 2022 showed how empirical analysis led towards general propositions about geographical distribution and regions, and how those propositions could inform education. This was a concrete mechanism of intellectual continuity. A research tradition persisted through the questions students learnt to ask and the relationships they were encouraged to seek in evidence.

The same university setting also supported approaches concerned with the detailed social experience of urban and regional change. The Urban and Regional Laboratory, URRlab, brought researchers together around metropolitan development, residential differentiation and spatial mobility. Prague and its surroundings offered an accessible setting in which suburbanisation and changing settlement relationships could be investigated repeatedly. The resulting work connected statistical description with questions about everyday life and the organisation of social environments. Its significance for a regional history of science lies in the formation of a continuing working group. Shared projects, seminars and student participation allowed a metropolitan research agenda to accumulate evidence and develop beyond the contribution of any one investigator.

Prague's concentration of expertise also supported regular international teaching. Charles University's department records cooperation with Dartmouth College from 1994 on courses concerning transformation in the Czech Republic and Central and Eastern Europe. A Summer

Seminar on Migration Studies developed through cooperation with the University of Massachusetts Lowell from 2016. These activities connected the interpretation of Czech experience with students and scholars trained elsewhere. They also widened the intellectual environment in which local research was discussed. The capital's role consequently included the organisation of encounters through which observations of Czech society could enter comparative geographical debate, alongside its responsibilities for national teaching and research.

Brno's historical climatology developed through a different relationship between local expertise and wider scientific questions. Researchers associated with Masaryk University, particularly Rudolf Brázdil and Petr Dobrovolný, combined documentary evidence with instrumental observations and other records of past climate. Archives supplied material that required both historical criticism and climatological interpretation. The programme could therefore sustain cooperation across disciplinary boundaries while remaining identifiable through its methods and subject matter. Its geographical base mattered because expertise and training accumulated there; the territory being reconstructed extended across the Czech Lands and into comparative European investigations. The centre became a place where locally accessible historical evidence could be evaluated within a much larger climatic context.

The European reach of this work was apparent in the 2005 review of historical climatology written by Brázdil with Christian Pfister, Heinz Wanner, Hans von Storch and Jürg Luterbacher. The authors considered the interpretation of documentary sources, climate reconstruction and relationships between weather and society. Such collaboration helped place Czech research within a common methodological discussion. It also shows why a scientific school should be understood as open to exchange: a coherent local programme could become stronger through comparison with work conducted elsewhere. Brázdil's receipt of the Vautrin-Lud Prize in 2020 provided a further indication of international recognition, although the underlying continuity depended on research and training sustained over many years.

Brno also supported connections between climatology, agriculture and research on global change. A 2021 study led by Miroslav Trnka examined changes in Czech agroclimatic zones over 1961–2019. Its affiliations brought together CzechGlobe, Mendel University, Masaryk University and international partners. The organisation of the study is as revealing here as its subject. Researchers could combine expertise in climatic variability with knowledge of crop environments and the interpretation of long observational records. Brno's concentration consequently took the form of overlapping institutional relationships. Several organisations contributed to a programme whose coherence came from a shared environmental question, rather than from membership of one department.

Geological research in Brno provides a parallel example involving shared equipment. In spring 2003, Masaryk University and the Czech Geological Survey established a joint Centre of Electron Microscopy and Microanalysis. The account published by Petr Sulovský, Renata Čopjaková and Radek Škoda in 2004 explicitly connected this arrangement with the integration of research, teaching and practical applications. A specialised analytical facility allowed geological investigations to draw upon common technical expertise and supported students' familiarity with advanced methods. The local concentration of a university and a national

survey thus had a material expression. Scientific cooperation was sustained through access to instruments and the knowledge required to obtain and interpret dependable analyses.

Masaryk University's polar programme extended the geographical reach of Brno still further. The project for an Antarctic station originated at its geography department in 1999. Construction was completed in 2006, and the Johann Gregor Mendel station on James Ross Island was formally opened in February 2007. Its programme included climate observation and investigations of glaciers, permafrost and ice-free terrain. The repeated organisation of expeditions required continuity in technical preparation and the training of researchers. Brno was therefore the organisational centre of a field programme whose principal research setting lay far beyond Czech territory. Its development demonstrates how a regional university could acquire an international responsibility through a sustained investment in a particular environment and its observation.

Olomouc illustrates the emergence of new specialisms within an established geographical centre. Geoinformatics became a separate department at Palacký University in 2001, under the leadership of Vít Voženílek. The subsequent development of cartography and geographical visualisation gave the centre a methodological profile that could serve many substantive fields. The university's chronology also records the opening of international development studies in 2003 and the separation of that department in 2007. This differentiation enlarged the range of geographical questions that could be pursued locally. It grew out of an existing educational environment, where new programmes and research interests gradually acquired their own institutional support.

The introduction of eye-tracking research in June 2011 made one aspect of the Olomouc specialisation particularly clear. Researchers used recordings of eye movements to investigate how people read and interpret maps. The method connected cartographic design with experimental investigation of perception, and it involved students in the preparation and analysis of studies. A map could be examined through the behaviour of its users, adding a different form of evidence to judgements about visual effectiveness. This was the formation of a research community around a transferable method. Its potential applications extended across the subject matter of geography because the communication of spatial information was itself an object of investigation.

The careers associated with Olomouc also reveal the circulation through which regional specialisation developed. Voženílek's training included mathematics and geography at Masaryk University and doctoral work in physical geography, followed by appointments and qualifications linking Olomouc with other Czech centres. His leadership of the geoinformatics department lasted from 2001 to 2022. This history connected the cultivation of a local programme with experience acquired elsewhere. It cautions against treating a regional school as intellectually self-contained. Researchers could bring methods into a centre, establish the conditions for their further development and maintain relationships through which subsequent work circulated beyond it.

In Ostrava, the transformation of an industrial region supplied a persistent set of questions for economic and social geography. Work by Petr Rumpel, Ondřej Slach and their collaborators

examined urban shrinkage, the governance of regeneration and the consequences of changes in employment and population. Their 2013 study with Jaroslav Koutský combined statistical evidence with interviews, workshops and observation in an analysis of Ostrava. The city was an accessible empirical setting, while the concepts belonged to a wider European debate. This combination gave regional research a comparative purpose. Detailed knowledge of local institutions and neighbourhoods could inform explanations of processes also occurring in other industrial cities.

Ostrava's physical geography developed a complementary concentration in geomorphology, hydrology and the investigation of natural hazards. The University of Ostrava's account of its research identifies dendrogeomorphology among its principal fields, using tree-ring evidence to examine landslides, floods and rockfall. Such work required field familiarity and specialist laboratory skills. The nearby Carpathian landscapes offered settings for repeated investigation, although the method could be applied in other regions. The resulting specialisation connected an understanding of particular terrain with the development of approaches capable of travelling beyond it. Regional expertise acquired scientific importance when findings from one landscape could be assessed against observations elsewhere.

The technical and geological traditions of the Ostrava region widened the same scientific environment. VŠB–Technical University of Ostrava maintained research concerned with mining, geological conditions and the measurement and management of industrially altered terrain. This brought engineering and subsurface expertise into proximity with university investigations of environmental and urban change. Proximity made collaboration possible without erasing differences in research purpose. A question about the future of a mining region could require an understanding of its physical condition as well as employment, settlement and public decision-making. Ostrava's contribution to Czech science thus drew on several bodies of expertise formed through the region's industrial history and subsequently reoriented towards new problems.

Pilsen developed a distinctive connection between geomatics and applied mathematics. The NTIS centre at the University of West Bohemia was built through a project running from December 2010 to December 2014, with new facilities constructed during that period. It became a research and development centre of the Faculty of Applied Sciences in 2015. Geospatial data processing and mathematical modelling formed part of its programme, alongside other technical and natural science fields. For geodesy, the importance of this development concerned the concentration of analytical expertise and the connection between research and advanced education. The new centre gave an existing university setting additional capacity to pursue methods relevant to the measurement and modelling of the Earth.

NTIS also illustrates how investment in a regional centre could strengthen a geographically distributed partnership. VÚGTK, based in Zdiby and operating the Pecný observatory, participated in the original project. The subsequent support programme for 2015–2020 included research in space and physical geodesy, using observations from Pecný and from stations elsewhere in the world. This relationship joined university modelling with specialised observational expertise. The resulting scientific arrangement crossed regional boundaries

from the outset. Its continuity also depended on support after the construction phase, when facilities and research teams had to be maintained and put to sustained use.

České Budějovice sustained another form of regional concentration through research on inland waters. A predecessor laboratory moved there in 1981 and became the autonomous Institute of Hydrobiology in 1990, before the period examined here. Its programme combined field investigation with experiments on reservoirs, lakes and their catchments. Its 2013 account emphasised eutrophication, water chemistry and the acidification and recovery of mountain lakes. These themes brought hydrological and chemical processes into contact with ecological research. Its contribution to the Earth sciences lay in treating a water body together with its catchment and the material flows influencing its condition.

Long-term investigations of reservoirs such as Římov and Slapy gave this programme a temporal depth that individual visits could not provide. The same account described research on nutrient sources, mixing and the interactions between physical conditions and biological communities. Continuing records allowed processes operating at different timescales to be distinguished. They also required the preservation of practical knowledge about sampling and the interpretation of particular sites. A regional research tradition could therefore be maintained partly through repeated responsibility for a field setting. The scientific centre and its study area developed together, even where the waters under investigation were dispersed across a wider basin.

Geography at the University of South Bohemia connected a different part of this regional environment with schools and public administration. Its Faculty of Education combined research in physical and human geography with preparation for teaching and work on regional development. Cooperation with schools gave local geographical knowledge a route into education, while links with public bodies connected research with practical territorial questions. These activities formed part of the reproduction of scientific expertise within a region. They helped maintain a community able to interpret geographical evidence and communicate it to users whose work lay outside specialised laboratories.

In Ústí nad Labem, the development of geography reflected both a long educational inheritance and a changing regional research agenda. The department's own history records Jiří Anděl's appointment as head in 1999 and its movement into the institutional setting that became the Faculty of Science in 2005. Subsequent work brought environmental processes into closer conversation with social and historical enquiry. The region's industrial and settlement changes offered important material for investigation, but local relevance did not confine the questions to northern Bohemia. Research on landscape transformation and risk could be connected with debates over planning, vulnerability and adaptation in other European settings.

Pavel Raška's career provides a particularly clear example of the connections involved. He completed geographical and historical studies at Ústí nad Labem in 2005 and a doctorate in physical geography at Masaryk University in 2011, before leading the Ústí geography department during 2015–2023. His research moved from landscape dynamics and geomorphological processes towards the historical and social dimensions of natural hazards. This trajectory connected training in one regional centre with the development of a programme

in another. It also showed how a research tradition could change through the combination of disciplinary experience, rather than simply being transmitted in an unchanged form from supervisor to student.

Liberec offered a further setting in which regional position could support a distinctive research question. Work on cross-border cooperation placed neighbouring territories and their institutions within the same field of enquiry. Hynek Böhm's 2021 investigation of the effects of the Covid-19 pandemic on Czech–Polish cooperation examined how temporary border closures affected established relationships. The study considered governance and regional development, including differences between border regions. It connected political geography with the practical operation of European integration. The regional significance of such research lay in sustained knowledge of borderland institutions and interactions, while its theoretical interest concerned the conditions under which connections across a national boundary could be interrupted or maintained.

The spatial organisation of Earth science observation introduces a further distinction between research centres and research locations. The western Bohemian seismic network WEBNET, registered as operating from 1991, maintained observations in a region of recurrent earthquake swarms. Its scientific operation connected field stations with Academy expertise based elsewhere, including Prague. The pattern followed the distribution of the phenomenon being investigated. A map showing university buildings alone would therefore understate the scientific importance of western Bohemia. Regional research activity also existed through instruments, recurring fieldwork and the maintenance of records, even where the principal institutional address lay outside the region.

CzechGlobe's infrastructure provided a comparable arrangement for research on environmental change. Facilities associated with its Brno base were distributed across the country. The atmospheric station at Křešín near Pacov, ecosystem stations and experimental facilities at Bílý Kříž and Domanínek served different environmental settings and purposes. Their distribution allowed researchers to investigate conditions that could not be represented adequately by one urban laboratory or field site. It also created connections between the work of specialist teams and the continuing operation of facilities elsewhere. The geography of the programme consequently included both the concentration of analytical skills and the deliberate dispersal of observation and experiment.

This dispersal had practical implications for the continuity of research. A new instrument could improve a measurement, while a long-established field site retained the context needed to interpret change. Technical staff and researchers familiar with a locality could recognise circumstances that were poorly recorded in a dataset. Regional expertise therefore included knowledge acquired through repeated work in a place. Its preservation depended on training successors and retaining enough documentation for later users to understand earlier choices. The expansion of national and European infrastructures increased the opportunities for comparison while making these local responsibilities more consequential.

Publishing created connections among regional communities that were different from those sustained by fieldwork. Moravian Geographical Reports began publishing in English in 1993

through the Brno geographical workplace of the Institute of Geonics, continuing an earlier journal tradition. It became exclusively electronic from 2020, and Palacký University's geography department joined as a co-publisher in 2023. These changes placed the maintenance of a geographical journal within a relationship between centres. An editorial community could provide a continuing setting for debate across physical and human geography while making research from different regions accessible to international readers. The regional origin of the journal thus coexisted with a much wider geographical reach.

Scientific meetings supplied a more temporary form of concentration. The Czech Geographical Society's annual conference in Ústí nad Labem in September 2024 adopted the theme Geography for Just Transformations. Its programme connected the location of the meeting with questions arising in coal regions and their transition towards a lower-carbon economy. Sessions brought together work that would otherwise be distributed among separate departments and research groups. Hosting the meeting gave the region an opportunity to shape a national conversation, while participants could compare their own approaches with problems made especially visible there. Conferences consequently contributed to the organisation of science through the movement of researchers and the selection of common questions.

The development of regional centres over the full period followed several overlapping rhythms. The 1990s brought reorganisation and the redirection of inherited expertise towards new social and environmental conditions. During the 2000s, specialist departments and shared laboratories gave some emerging fields more durable institutional support. European investment subsequently enlarged the capacity of centres such as NTIS, while the later period saw existing groups connected through more extensive infrastructures and collaborative programmes. These developments did not produce an even distribution of resources. They created additional combinations through which a smaller centre could sustain work of wider significance and a large concentration of institutions could draw upon expertise located elsewhere.

Scientific schools also differed in the resources on which their continuity depended. Historical climatology required skills in the criticism and interpretation of records; experimental cartography depended on the design of studies with map users; analytical geology required both instruments and expertise in their operation. An interruption in staffing or support could affect these traditions in different ways. A regional history therefore needs to attend to the knowledge carried by researchers and technicians, alongside the visible expansion of buildings and equipment. The examples considered here show how new capacity became scientifically productive when it was connected with research questions and the education of people able to pursue them.

For international research and training, this pattern made the working group and its relationships particularly important. A specialised project might require cooperation with one laboratory, access to a field station in another region and guidance from researchers whose own training crossed several institutions. The relevant scientific environment could extend well beyond the host city's administrative boundary. By 2025, Czech geography and the Earth sciences offered a differentiated set of such environments. Their regional character remained

visible in accumulated expertise and continuing engagement with particular places, while collaboration enabled that experience to contribute to questions of national and international scope.

Research Funding, Scientific Societies, Academic Journals and International Cooperation

Between 1993 and 2025, Czech geography and the Earth sciences developed through a changing relationship between financial support, professional association and the circulation of knowledge. Competitive grants gave researchers opportunities to define new investigations, while institutional funding sustained the organisations in which those investigations could be undertaken. Scientific societies brought together colleagues employed by different institutions, and journals gave their results a continuing public record. International cooperation connected these activities with research questions and resources beyond the country. Their combined effect was to make scientific development depend increasingly on relationships that crossed the boundaries of a single university, institute or national funding scheme.

The distinction between institutional and project funding is particularly important in the geographical and observational sciences. An investigation of river behaviour may have a defined beginning and end, although its interpretation can depend on measurements collected over several decades. A geological project may use collections and analytical facilities maintained for many other purposes. Institutional support provides part of this continuing capacity, whereas a grant usually attaches resources to a specified question and period of work. The two forms of support therefore meet within the same research programme. Their relationship helps explain why the award of a project and the preservation of a scientific capability are different achievements.

The establishment of the Czech Science Foundation, GAČR, in 1993 gave the new state a principal instrument for competitive support of basic research. Its remit extended across scientific fields, with applications submitted by experienced researchers and those at earlier stages of their careers. Investigators proposed their own subjects, and assessment involved disciplinary panels and external reviewers. For geography, this arrangement created a route through which questions about environmental processes or social differentiation could be presented on their scientific merits. It also required researchers to explain how an investigation would advance knowledge and how the proposed methods and expenditure would serve that purpose. The preparation of a grant application became part of the work of building a research agenda.

The range of GAČR instruments subsequently widened. EXPRO offered longer support for ambitious investigations, while JUNIOR STAR was designed to help promising researchers establish scientific independence and their groups. The latter scheme was introduced through competitions beginning in 2020 and provided five-year support. Individual postdoctoral

fellowships, first advertised in 2021, added opportunities for international mobility, including an outgoing arrangement combining work abroad with a subsequent period at a Czech institution. These instruments addressed different points in a scientific career. Their relevance to the geographical sciences lay in the possibility of connecting an individual research proposal with the formation of a team, access to methods and experience gained in another scientific environment.

The EXPRO awards for 2025 provide a concrete Earth science example. Jan Burjánek at the Institute of Geophysics received support for an investigation of volcanic activity on Iceland's Reykjanes Peninsula. The research plan combined records from the REYKJANET seismic network with fieldwork, geophysical surveys and modelling to examine the movement and storage of magma beneath the peninsula. A Czech grant thus supported a programme requiring sustained engagement with an environment outside the country. At the closing date of this history, its significance lay in the investigation made possible by the award and the methods and expertise assembled for that purpose.

Applied research acquired a different organisational centre with the establishment of the Technology Agency of the Czech Republic, TAČR, in 2009. The agency was intended to simplify and coordinate public support for applied research and experimental development, including cooperation between research organisations and users of their results. This remit was especially relevant to work on environmental management, territorial development and the consequences of industrial activity. A project concerned with groundwater protection or the interpretation of spatial information could be assessed partly through the use to which its findings would be put. The distinction from basic research concerned the programme's purpose and expected application; in practice, both types of investigation could draw upon the same expertise.

Environmental research illustrates how changes in programme design affected opportunities within a particular field. A 2020 account by researchers at the T. G. Masaryk Water Research Institute recalled the end of the Ministry of the Environment's dedicated programme in 2013 and the subsequent use of programmes with other priorities. The government approved Prostředí pro život, or Environment for Life, in March 2019, with TAČR administering the competition. The institute reported that six supported projects could begin in 2020. This sequence reveals the importance of an explicitly environmental programme alongside the availability of more general applied research support.

One of those projects examined the effects of atmospheric deposition on aquatic environments under different climatic conditions. It linked the Water Research Institute with the Czech Hydrometeorological Institute and the Silva Tarouca Research Institute for Landscape and Ornamental Gardening. The scientific problem required evidence about pollutants moving between air, land and water, together with an understanding of earlier contamination. Programme funding could thus assemble expertise distributed among several organisations. The example also shows how an applied objective could require an investigation of environmental processes whose explanation crossed conventional disciplinary boundaries.

European structural funding supported another kind of scientific development by enlarging the capacity available to research teams. Within CzechGeo/EPOS, support from the Operational Programme Research, Development and Education was directed towards completing and upgrading observatories and networks, alongside research using the improved infrastructure. The activities included GNSS and gravimetry as well as investigations of seismicity and lithospheric structure. Such investment differed from the funding of an isolated investigation. It could improve the conditions under which several later projects would be undertaken, provided that the instruments, data services and necessary expertise continued to receive support after the investment phase.

The launch of the Excellent Research call under the Johannes Amos Comenius Programme in July 2022 continued the use of European funds to develop research capacity. The programme followed the earlier Operational Programme Research, Development and Education and sought to strengthen scientific teams and their work on substantial research problems. For a history extending to 2025, its significance lies in this continuation of investment alongside national grant competitions. Modernising equipment could be combined with the development of research teams and their mobility, linking resources more closely with the work they were intended to support. The resulting system offered several routes to support, each carrying its own timetable and expectations.

The assessment of institutions changed as well. Methodology 2017+, approved by the government in February 2017, combined evaluation of research results with attention to social relevance, institutional viability and strategy. Its framework distinguished universities, Academy institutes and departmental research organisations, whose responsibilities were not identical. Quantitative evidence was used together with expert assessment. The methodology consequently allowed institutional support to be considered in relation to an organisation’s purpose and development, alongside its publication performance. For geographical and Earth science organisations, this was a consequential distinction: the maintenance of observations, the preparation of maps and the provision of expert services could have importance that a count of articles alone would describe poorly.

These funding arrangements created opportunities without removing the need for continuity. Project competitions encouraged researchers to formulate new questions and demonstrate the value of their methods. Long observational series, however, required the preservation of knowledge and records through successive projects. A laboratory also depended on staff able to maintain equipment and recognise unreliable results. The history of support therefore needs to be read at more than the level of individual awards. An institution’s capacity to carry work from one project into another was central to the development of sustained research, especially where environmental change could only be understood through repeated observation.

Scientific societies supplied a different form of continuity. The Czech Geographical Society’s history records that the closure of the Academy’s Geographical Institute in April 1993 deprived it of material and organisational assistance. Nevertheless, the society continued its activities and marked its centenary with a congress in Prague in May 1994. This experience illustrates the practical importance of professional association during institutional change. A society could maintain discussion among geographers whose employment and research arrangements were

being reorganised, while providing a recognised setting in which the discipline could consider its collective responsibilities.

The society's publications served different parts of that community. *Geografie* provided a venue for research articles, while *Informace České geografické společnosti* combined scientific contributions with reviews and news from geographical institutions. *Geografické rozhledy* connected university geography with teachers, students and other readers interested in geographical education. The Geographica series offered space for scholarly monographs. Together, these activities supported several stages in the movement of knowledge, from specialised investigation to discussion within the profession and communication in education. Their coexistence also preserved room for work whose most appropriate form was a substantial study or an explanation for teachers, rather than a short article intended primarily for an international research audience.

Greater specialisation also produced new forms of association. The Czech Association of Geomorphologists was formally founded in January 1999, following the work of the Czech Geographical Society's geomorphological commission. The group had already been registered as a national partner of the International Association of Geomorphologists in 1994. Its history therefore connects the consolidation of a specialist community with international representation. An organisation devoted to geomorphology could concentrate discussion on the interpretation of landforms and processes while bringing together researchers based in different departments. The emergence of such an association added to the ways in which a researcher could belong to the wider geographical community.

Atmospheric scientists maintained a comparable relationship between an inherited professional community and a new national framework. The Czech Meteorological Society took its Czech form in 1993, continuing the earlier Czechoslovak organisation. Karel Krška's historical account, published in 2009, emphasised its regional groups, specialist discussion and work on terminology. The explanatory meteorological dictionary published in 1993 was a substantial expression of this responsibility for the language of the subject. The society also participated in the establishment of the European Meteorological Society in 1999. Professional association consequently linked scientific exchange within the country with a European setting in which meteorology and climatology could be discussed across institutional and national boundaries.

Cartography offers a particularly clear example of cooperation surviving the division of the state. Separate Czech and Slovak cartographic societies emerged in 1993, but from 1995 their conferences were organised jointly and alternated between the two countries. The sequence continued through the Pilsen meeting in 2013. From 2015, the biennial conference series was held within the Czech Republic, and the Czech society adopted its present name that year. The 26th conference took place in Brno in September 2025. This chronology shows how a shared professional tradition could acquire separate organisational forms while retaining a substantial period of common scientific activity after 1993.

In geology, the relationship between a society and international cooperation was made explicit in a 1994 agreement concerning the Czech National Committee for UNESCO's IGCP

programme. The committee associated with the Czech Geological Society, which possessed the legal identity and national professional coverage needed to support its activities. The agreement addressed coordination, conferences and assistance with research and publication. Such arrangements mattered because international scientific participation required practical administration as well as individual expertise. A voluntary professional organisation could provide a home for cooperation extending across universities, Academy institutes and the geological service, without becoming the employer of the researchers involved.

Academic journals gave these communities another means of maintaining scientific standards and exchanging results. Editing and reviewing required researchers to judge evidence produced beyond their working groups. Authors, in turn, had to make methods and explanations intelligible to readers who had not participated in the investigation. During the period considered here, Czech journals developed different responses to internationalisation. Some gave greater prominence to English and international reviewing, while others preserved Czech and Slovak as languages of scientific and professional exchange. Electronic publication widened access across this range of audiences, although the work of selecting, reviewing and preparing articles continued to depend on people and institutional support.

Geografie illustrates the connection between an established national journal and international recognition. The Czech Geographical Society records its inclusion in Web of Science from 2008, and the journal's title was shortened to *Geografie* in 2010. Its editorial procedures provided for anonymous reviewing, with manuscripts considered in English as well as Czech and, under specified conditions, Slovak. This combination made room for geographical scholarship addressing Czech circumstances while exposing it to assessment beyond an author's immediate professional circle. The journal's development also made international visibility compatible with an institutional commitment to the national geographical community.

Moravian Geographical Reports provided an English-language venue covering both human and physical geography. Its electronic distribution expanded through the De Gruyter/Sciendo platform from 2013, and it became exclusively electronic in 2020. The journal's non-commercial open-access model made the financing of publication especially visible as an institutional responsibility. Its publishers and editorial community sustained a service through which research could circulate without subscription barriers. This mattered for readers in smaller institutions and for researchers investigating Central and Eastern European problems, whose work could enter international discussion through a journal attentive to that regional context.

The geological journals underwent a particularly explicit reorganisation of language and subject matter. In 1993, the former *Časopis pro mineralogii a geologii* became the *Journal of the Czech Geological Society*, adopting English and more demanding reviewing procedures for an international readership. Online tables of contents followed in 2001 and PDF articles in 2003. A subsequent agreement with the Czech Geological Survey divided editorial responsibilities more clearly. From 2006, palaeontology, sedimentology and related subjects were directed towards the *Bulletin of Geosciences*, while the society's journal concentrated

on crystalline geology and associated fields. Its relaunch as the *Journal of Geosciences* in January 2007 gave a new title to a substantial change in scientific purpose and publication practice.

This division created complementary venues within a relatively small national scientific system. The *Bulletin of Geosciences* maintained an international scope centred on palaeoenvironmental geology and entered Web of Science coverage from its first issue of 2007. *Studia Geophysica et Geodaetica*, associated with the Institute of Geophysics, connected work in geophysics and geodesy with meteorology and climatology. The continued availability of such journals allowed results requiring different methods and specialist readerships to find appropriate editorial assessment. Their importance lay partly in the preservation of expert communities capable of evaluating work across fields that were institutionally distributed among several organisations.

Professional journals also kept research close to the circumstances in which knowledge was used. *Meteorologické zprávy* provided a setting for discussion within the hydrometeorological community, including historical reflection on the organisation of the subject. In water research, *VTEI* linked scientific investigation with the concerns of water management. It appeared as a separate supplement to *Vodní hospodářství* between 1999 and 2015, before resuming independent publication with its website. From 2022, a complete English version of its scientific content was also published online. The journal's development extended the reach of applied work while retaining Czech and Slovak communication with practitioners and public bodies.

Geodesy and cartography retained a further channel of shared professional communication in *Geodetický a kartografický obzor*. The journal continued joint Czech and Slovak publication after 1993 and moved to exclusively electronic publication in 2013. Its readership included researchers and teachers alongside specialists in public administration and commercial practice. This was an important conjunction for subjects in which scientific methods interacted with surveying standards, cadastral work and the production of geographical information. A common periodical helped preserve discussion across the new state boundary and between research and professional application. Its history provides a useful counterpoint to accounts that measure internationalisation principally through the adoption of English.

The significance of electronic publication extended beyond the convenience of obtaining an article. Searchable archives made earlier work easier to recover, allowing a later investigation to examine the history of a method or the interpretation of a particular locality. English versions and supplementary materials could make nationally produced evidence more usable elsewhere. Yet access to a published explanation remained distinct from access to the observations on which it depended. A journal archive and a research data service performed related tasks, each requiring continuing care. The development of open publication therefore formed part of a wider change in how scientific knowledge could be preserved, inspected and reused.

International cooperation had visible occasions as well as continuing organisational forms. The IGU regional conference held in Prague in August 1994 brought approximately 1,200

geographers together, with Charles University's geography section carrying much of the organisational responsibility. Its timing is instructive. A major international gathering took place soon after the establishment of the Czech Republic and during significant institutional reorganisation. It enabled direct discussion of Czech and Central European experience within a wider geographical community. Such meetings supplied opportunities for relationships that could later support comparative research and publication.

European project funding subsequently gave some of those relationships a more sustained working form. SHRINK SMART, funded through the Seventh Framework Programme from May 2009 to April 2012, included the University of Ostrava in a consortium coordinated by the Helmholtz Centre for Environmental Research in Leipzig. Eight universities and research institutions investigated the governance of urban shrinkage through comparative studies. Ostrava's participation connected knowledge of a Czech industrial city with work in other European settings. The project required partners to formulate questions and produce evidence that could be compared, thereby making international cooperation part of research design and the interpretation of findings.

In geology, GeoERA brought national and regional geological surveys into a common research framework under Horizon 2020. The project ran from January 2017 to February 2022, with the Czech Geological Survey among its participants. Its arrangements combined European Commission support with contributions from the survey organisations themselves. The subjects included groundwater, geoenergy and raw materials, together with the development of interoperable information services. Cooperation consequently concerned the compatibility of evidence as well as the exchange of findings. National geological knowledge had to be expressed through approaches and data arrangements that would allow it to contribute to a wider European understanding of the subsurface.

By the closing years of this study, that work was continuing through a further generation of cooperative projects. The Czech Geological Survey's report for 2024 described its participation in Geological Service for Europe, GSEU, which had begun in 2022. Its contribution included geoenergy research and the preparation of information on geothermal resources and underground storage for incorporation into the European Geological Data Infrastructure. This provides a concrete example of an international programme becoming connected with continuing institutional responsibilities. Research could contribute to a shared European resource while drawing on expertise and information maintained within the national geological service.

Cooperation in observation also depended on formal international commitments. The Czech Republic signed a framework agreement with the European Space Agency in 1996, entered the Plan for European Cooperating States in 2004 and signed its accession agreement in 2008. In 2010 it became a full member of EUMETSAT. These developments placed Czech participation in space-based observation within a more durable institutional framework. Their relevance extended across meteorology, climatology and the use of satellite information in geographical research. They also connected national expertise with systems whose construction, operation and interpretation required resources and cooperation on a scale extending well beyond one country.

International basic research acquired a further mechanism through the Weave initiative announced by GAČR in 2021. Researchers could prepare a joint proposal assessed by a lead funding agency, with the participating national agencies responsible for supporting their eligible researchers. The initiative used existing funding channels and simplified the coordination of assessment. Its early Czech partners included agencies in Austria, Germany and Poland, as well as other European countries. This arrangement was relevant to questions extending across boundaries, whether concerning a geological structure, an environmental process or a social relationship. A common scientific plan could be supported through coordinated national decisions rather than separate, unrelated applications.

Cooperation also had to respond to threats to the continuity of scientific work. In March 2022, following Russia's invasion of Ukraine, the Czech Academy of Sciences announced the Researchers at Risk Fellowship programme, initially directed towards researchers from Ukraine. Academy institutes could propose the incorporation of scientists and doctoral researchers into their teams. The programme covered all research fields; its relevance to the geographical and Earth sciences was therefore part of a wider framework for preserving scientific activity under conditions of displacement. This episode adds another purpose to international mobility, alongside training and project collaboration: enabling researchers to continue their work when remaining in their previous institution had become impossible or unsafe.

Across these developments, international participation required decisions about what should be shared and how it should be communicated. A geological interpretation might need internationally comparable classifications, while a study of settlement change could depend on careful explanation of Czech administrative categories. Work intended for local water managers could require a different presentation from an article addressing an international methodological debate. The coexistence of Czech, Slovak and English publication was therefore connected with the different uses of scientific knowledge. A productive research system needed routes through which findings could travel between those audiences without losing the circumstances necessary to understand them.

The history from 1993 to 2025 shows a widening range of arrangements through which research could be supported and assessed. National grant competitions established a durable place for investigator-defined projects, while applied programmes connected scientific expertise with public and economic needs. European investment enlarged research capacity and supported comparative work. Societies and journals maintained relationships that could outlast an individual award, and international funding mechanisms made some of those relationships easier to organise. Their contribution to scientific development depended on how well they worked together within particular programmes of enquiry.

For an international researcher or student, this history offers a practical way of understanding a prospective scientific environment. The relevant questions concern the continuity of the working group, the resources supporting its investigation and the professional discussions in which its results are assessed. A journal or society can reveal relationships that are less visible in an institutional directory, while a sequence of projects can show how a research question has developed over time. By 2025, Czech geography and the Earth sciences could be

approached through these connected records of support, association and cooperation. They explain how specialised research was sustained and how its findings reached informed readers.

Strengths, Uneven Development, Institutional Challenges and the Training of New Researchers

By 2025, Czech geography and the Earth sciences possessed substantial scientific capabilities, although the conditions under which those capabilities developed remained uneven. Established research traditions had produced methods and explanations useful beyond the country, and newer centres had widened the range of specialised work. Their continuity depended on arrangements for observation, collaboration and the education of successors. The evidence considered in this chapter supports a differentiated assessment. Scientific achievement could coexist with difficulties in recruitment or coordination, while the creation of a well-equipped workplace did not by itself establish a durable research community. The training of new researchers brings these relationships into particularly clear view.

An assessment of strengths must begin with the purposes of the work being assessed. A geological survey maintains information that may be used long after its collection, whereas a university research group may concentrate on developing an explanation of a particular process. Both can contribute to scientific progress, through different responsibilities and timescales. The relevant evidence includes the quality of published findings and the capacity to preserve and interpret observations. It also includes the formation of researchers able to question earlier explanations. These criteria provide a more useful basis for comparison than institutional size or the presence of a fashionable method considered in isolation.

Historical climatology demonstrates how accumulated expertise could become a source of international scientific strength. The European review published by Rudolf Brázdil and his collaborators in 2005 connected the interpretation of documentary evidence with climate reconstruction and the study of relationships between weather and society. Such work required historical criticism alongside climatological knowledge. A record of an unusual season had to be evaluated in relation to its author, purpose and circumstances before it could contribute to an account of climatic variability. The achievement therefore rested partly on a method of reasoning that others could inspect and apply. Preserving that capability required the transmission of interpretative skills as well as access to archives.

Human geography likewise contributed explanations capable of travelling beyond their original empirical setting. Luděk Sýkora and Stefan Bouzarovski’s 2012 account of urban transition connected institutional change, social transformation and the reorganisation of urban space. Its significance lay in explaining why these processes operated at different speeds and how their relationships shaped post-communist cities. Czech experience contributed to a conceptual framework relevant to a wider group of countries. This example identifies a

particular kind of strength: detailed knowledge of a place became useful in constructing an explanation that could be examined elsewhere. International participation could consequently involve the development of theory as well as the application of concepts formulated abroad.

External evaluation reveals differences within institutions. The Academy's assessment of the Institute of Geonics for 2015–2019 recognised the Environmental Geography team's work on brownfield regeneration and its contributions to research on the spatial behaviour of disabled people. It also identified limitations in the wider institute's capacity to assemble large teams and recruit researchers and doctoral students. These findings describe achievement and institutional vulnerability within the same organisation. The assessment of an institute therefore needs to be read alongside evidence about its individual groups and their scientific responsibilities.

The corresponding evaluation of the Institute of Atmospheric Physics recognised work extending from processes near the Earth's surface to the upper atmosphere and planetary environments. Its combination of observation, theory and modelling supported investigations across markedly different spatial and temporal scales. The reviewers also emphasised the need to continue the long observational record at Milešovka. In this case, scientific breadth was connected with specialist expertise and continuing responsibility for instruments and records. The value of a research institution included the capacity to connect these activities, allowing observations made for one purpose to contribute to questions arising later.

National scientific services added another source of continuity. The Czech Hydrometeorological Institute's report for 2024 documented an observational system encompassing surface conditions, water and the vertical structure of the atmosphere. Aerology formed part of this wider meteorological organisation, contributing evidence that measurements at ground level could not supply. For climatology and hydrology, the existence of continuing records created opportunities to distinguish exceptional events from longer changes. Their scientific value depended on the circumstances of measurement remaining intelligible. Maintaining the network therefore involved a continuing investment in technical knowledge and documentation, alongside the collection of additional data.

Uneven development consequently had several meanings. Specialisation reflected the questions for which particular groups had acquired expertise, while differences in resources affected the scale and continuity of the work they could undertake. An experimental facility required substantial technical support; a theoretically ambitious investigation could depend more heavily on time for reading, discussion and comparison. Neither form of work was inexpensive in the broader sense of the attention and experience it required. A national system capable of accommodating both had to recognise their different conditions. Comparisons become misleading when one institutional model is treated as an adequate description of every branch of geography or the Earth sciences.

The intellectual consequences of earlier isolation were already being discussed during the first decade of the new state. Ivan Bičík and Martin Hampl's assessment of Czech human geography in 2000 examined its research orientation in relation to international geographical thought and the changes following 1989. Their discussion also addressed the subject's

relationship with social and environmental sciences. The problem of constructing coherent geographical explanations thus accompanied the expansion of international contact from an early stage. Access to a wider literature created opportunities, while the interpretation and development of that literature required sustained argument within the scientific community.

An intervention by Roman Matoušek, David Vogt and Jan Ženka in 2011 gave this concern a sharper expression. Writing from a human geographical perspective, they criticised thematic fragmentation and the limited extent to which individual studies accumulated into a shared body of explanation. Much research, they argued, remained confined to Czech localities without sufficient theoretical development or comparison. Their proposed response was a discussion of substantial research questions around which findings could become connected. This was a contemporary argument within the discipline. Its historical importance lies in the explicit demand that geographical research should build on earlier work through intellectual engagement, beyond the addition of another local case.

Vincenc Kopeček, Tomáš Drobík and Jana Hasalová extended the same period's discussion towards the public purpose of human geography. They argued for greater sensitivity to social change and for research agendas that could examine political relationships and the experience of people. Their contribution raised questions about how topics were selected and whose concerns geographical enquiry should address. Such arguments belonged to a debate over scientific responsibility, rather than a single agreed programme for the whole discipline. They nevertheless show that methodological modernisation was accompanied by disagreement about the purposes for which new approaches should be used.

These discussions help distinguish productive diversity from fragmentation. Different methods can enrich an investigation when their relationship to a common question is made clear. They contribute less to cumulative understanding when researchers cannot establish how their findings connect with work undertaken elsewhere. The difficulty is especially pertinent to studies combining environmental and social processes, where the evidence may take very different forms. A shared project title or digital platform provides limited intellectual integration on its own. Researchers also need to explain how measurements, historical records or accounts of human experience bear upon the explanation being developed.

Institutional arrangements could make that integration difficult. The Environmental Geography section of the Geonics evaluation reported that the division of national funding panels into fields complicated support for work connecting different research communities. Its reviewers also discussed administrative demands and the need for adequate assistance with project management. These were practical conditions affecting how an interdisciplinary programme could be sustained. Expertise spanning several subjects required institutions able to support its organisation, alongside researchers prepared to conduct it. They were practical difficulties identified within a specific assessment period.

The Atmospheric Physics evaluation identified another institutional problem. Research themes overlapped with those of the hydrometeorological service, CzechGlobe and Charles University, and the reviewers recommended closer cooperation. They also expressed concern about the security of long-term funding for observatories. Together, these observations

exposed a difficulty that organisational diagrams describe poorly. Related expertise could exist in several institutions while the arrangements for using it jointly required further work. Equally, the continued operation of an observatory needed recognition as a sustained responsibility, with a timescale extending beyond the investigation supported by an individual grant.

Evaluation itself involved questions of appropriate comparison. In his published response of June 2021, the Atmospheric Physics director, Radan Huth, challenged aspects of the treatment of individual departments. Among his concerns were the description of contributions to research on upper-atmospheric trends and expectations about teaching subjects outside a department's expertise. The exchange illustrates the judgement involved in assessing specialised science. An evaluation had to understand what a group was equipped to contribute and how that contribution should be represented. Publication of both the assessment and the institutional response made this reasoning available for examination.

The position of doctoral researchers connects these intellectual and organisational questions. Robert Osman, Jan Trávníček, Jakub Trojan and Ondřej Konečný's contribution to the 2011 geographical debate was written from their experience as doctoral students. They questioned divisions between physical and human geography, and between research and geographical education. Landscape and agriculture supplied examples through which they explored alternative ways of understanding established topics. Their intervention treated doctoral researchers as participants in the development of geographical thought. The preparation of successors therefore involved creating opportunities for them to challenge conventions as well as to acquire the methods of an existing school.

Formal study arrangements provided a framework for that participation. The physical geography and geoecology guide at Charles University presents doctoral work as a contribution to international scientific knowledge, organised through an individual study plan. Its model includes discussion of aims and methods at departmental seminars, subsequent presentations of progress and the publication of findings. These stages make the development of an investigation open to scrutiny before the final defence. Their educational value depends on the quality of the discussion: a presentation becomes part of research training when colleagues examine the connection between the question, the evidence and the proposed explanation.

Geodesy illustrates the continuing importance of disciplinary foundations within this process. Brno University of Technology's English-language doctoral programme in Geodesy and Cartography for 2024/2025 combined doctoral seminars with advanced study options in measurement analysis, geodesy and spatial data acquisition and processing. Its structure connected a specialised investigation with the mathematical and technical knowledge required to assess results. A researcher using sophisticated instruments still needed to understand the assumptions built into their operation and the subsequent analysis. Doctoral education thus preserved a role for sustained theoretical preparation alongside the practical use of increasingly capable equipment and software.

The development of specialist training also extended beyond the oldest geographical centres. Palacký University's geoinformatics archive records the successful doctoral defences of Jan

Caha and Aleš Vávra in November 2014. This provides evidence of an environment already capable of taking specialised research through to completion. The significance of such developments lies in the gradual reproduction of expertise within a regional centre. A department's contribution could grow through graduates able to teach, investigate new questions and participate in cooperation elsewhere. The establishment of a programme acquired scientific substance through the work completed within it and the capabilities its graduates carried forward.

The relation between technical instruction and scientific judgement was particularly clear in field-based subjects. The University of Ostrava's account of physical geographical research in 2017 identified dendrogeomorphology and investigations of landslides, floods and rockfall among its specialisms. Training for such work required an understanding of how evidence from a landscape could be collected and interpreted. A numerical result obtained from samples had to be related to the conditions under which those samples were selected. The wider educational task was to make the chain of reasoning visible, including uncertainty and the limits of an explanation. Technical competence became scientifically productive through that capacity for judgement.

Faculty initiatives sought to support capabilities shared across specialisms. Charles University's STARS measure of 2019 combined additional financial support with advanced methodological and professional education. It provided for courses in scientific writing, programming and data management, alongside opportunities to develop international professional relationships. Its funding arrangement joined a faculty contribution with support from the research team or department, including responsibility for continuity if a team's resources were exhausted. The measure connected doctoral education with institutional commitments extending beyond the enthusiasm of a prospective supervisor. It also recognised that successful scientific work required skills that could be taught across several doctoral programmes.

National policy documents acknowledged substantial weaknesses in doctoral education. Prepared in June 2020, the Ministry's strategic plan for higher education from 2021 reported an overall doctoral success rate of around 40 per cent and an average duration of successful study approaching five and a half years. These figures concerned doctoral education across fields and provide a national context for the geographical sciences. The plan sought more selective admission, better support and more effective supervision. It identified completion and the conditions enabling it as institutional responsibilities, alongside the scientific quality expected from the dissertation.

Supervision received more explicit professional attention during the later part of the period. In October 2023, the Student Chamber of the Council of Higher Education Institutions and the Czech Association of Doctoral Researchers proposed a Standard of Supervision in Doctoral Education. Their model addressed agreement on research goals and funding, constructive feedback and procedures for resolving difficulties or changing supervisors. It also treated supervision as work requiring time and institutional recognition. The document was a proposal for the development of university regulations. Its importance as historical evidence lies in the

effort to define relationships that had considerable influence over a doctoral researcher's ability to progress.

Clear expectations mattered especially where doctoral students also contributed to teaching or a larger project. Charles University's physical geography guide describes students as members of the department's scientific activities who also participate in education. These responsibilities could provide valuable experience, while the dissertation still needed a feasible allocation of time. Training depended partly on how duties were coordinated and explained. Regular review could help identify a problem while an investigation remained capable of adjustment. It could also make a student's developing independence visible through the decisions they learnt to justify, rather than through the completion of tasks alone.

Financial conditions became a particularly visible concern in 2025. The amendment of the higher education framework introduced a guaranteed doctoral study income linked to 1.2 times the minimum wage for eligible new full-time entrants. Masaryk University's implementation specified a minimum monthly doctoral study income of CZK 24,960 for the 2025/2026 academic year and extended its guarantee to qualifying existing full-time students. Scholarships and relevant employment income could contribute under defined arrangements. The change expressed a stronger expectation that doctoral researchers should have resources allowing them to concentrate on their work. Its longer-term effects on admission and completion extended beyond the closing year considered here.

An Ostrava recruitment document from 2025 shows how these arrangements could meet a particular geographical research agenda. It advertised one doctoral place in political and economic geography within REFRESH, supported through the Operational Programme Just Transition. The proposed investigation concerned development paths in old industrial regions. The position combined a four-year doctoral programme with participation in fieldwork, analysis and publication within a research team. Its significance here is as a documented model of recruitment and training. It made the relationship between the dissertation and a funded collective investigation explicit, while setting out expectations concerning language and research experience.

Developing independent researchers required care. A funded project could provide access to evidence and sustained discussion with experienced colleagues. The doctoral researcher still needed a question whose treatment involved an identifiable intellectual contribution. Agreement on that contribution was part of the educational relationship described in the supervision proposals. The issue became especially important where the student's work served several purposes at once, contributing to the team's results while forming the basis of an examined dissertation. A well-designed research environment could make those purposes compatible through clear responsibilities and recognition of authorship.

Access to scientific careers also depended on the working environment. The Institute of Geophysics reported that women accounted for 22 of its 76 scientific staff at the beginning of 2022. Its Equal Opportunities Plan addressed career development, under-representation and the relationship between employment and family life. These figures describe a particular institute and workforce, while the plan documents an institutional response to the conditions

under which people could enter and remain in research. Its proposed measures concerned the organisation of scientific employment as well as recruitment. Assessing their success would require evidence of implementation, beyond the existence of the plan itself.

International openness brought related responsibilities. The Ministry's strategy for the period from 2021 supported movement between universities and the recruitment of foreign doctoral candidates as ways of widening scientific experience and reducing academic inbreeding. The value of such movement depended on what researchers encountered at their new institution and whether their experience could subsequently be used. A visit could introduce a method or begin a continuing collaboration; its contribution to development grew through opportunities to discuss and apply what had been learnt. Mobility was therefore connected with the capacity of a working group to receive new ideas and allow them to affect its research.

The transition after the doctorate introduced a further test of institutional strength. A completed degree established a capacity for independent research, while subsequent employment required an organisation able to make use of that capacity. The recruitment difficulties identified in the Geonics evaluation show that sustaining a group involved more than the existence of a formal training route. Scientific responsibilities also extended beyond universities, through national services and applied research organisations. Careers in these settings could preserve specialised knowledge and connect it with practical problems. The development of new researchers consequently needs to be considered across the wider system in which their skills could be used.

For international and distance research training, published work and institutional documentation offer valuable material for examining these relationships. A participant can follow how a question was formulated, consider the evidence used and compare an author's explanation with an external assessment. The geographical debates of 2011 are particularly useful because they reveal researchers discussing the purposes and methods of their own discipline. Programmes and supervision documents make another part of scientific practice available for analysis. Read together, these sources allow research training to address the organisation of enquiry and the formation of judgement, alongside familiarity with findings or software.

The balance of evidence for 1993–2025 is therefore one of selective achievement and continuing institutional adjustment. Openness after 1989 and the establishment of the new state created conditions for reorientation. Subsequent specialisation and investment enlarged the work that could be undertaken, while researchers and evaluators continued to question how its parts should be connected. During the closing years, doctoral support and supervision became more explicit subjects of reform. These developments affected the capacity of scientific groups to maintain their work and enable their successors to contribute to it.

The strengths of Czech geography and the Earth sciences were most clearly expressed where expertise accumulated around questions that remained open to revision and comparison. Their uneven development reflected differences in purpose and resources, as well as difficulties acknowledged in the scientific community's publications and evaluations. Preparing new researchers was central to the relationship between those achievements and

constraints. By 2025, the institutional system could support specialised investigations of considerable reach; its durability depended on preserving the conditions under which new colleagues could understand that work, examine its assumptions and develop questions of their own.

Part Three

Physical Geography, Landscape Research and Geoecology

Physical Geography after 1993: Scientific Traditions, Systems Approaches and Methodological Renewal

Physical geography in Czechia developed after 1993 through the renewal of an established concern with the relationships that make places environmentally distinct. Its practitioners inherited detailed knowledge of landforms and regional environments, together with approaches that treated the landscape as an interconnected whole. During the following three decades, they acquired more precise ways of observing change and testing explanations. The resulting development joined regional expertise to increasingly specialised investigations of processes. By 2025, the central scientific question concerned how to connect these detailed findings across space and time, particularly where environmental change involved several interacting causes.

The inheritance itself had several sources. Miloslav Lapka and Miroslav Gottlieb's historical investigation, published in 2022 and informed by archival work and interviews, identified distinct centres of landscape ecology associated with Emil Hadač and with the Brno tradition of Antonín Buček and Jan Lacina. Their account helps explain why Czech landscape research cannot be reduced to a single disciplinary lineage. Geographers shared questions about environmental relationships with botanists and ecologists, while the cultural character of the countryside brought human activity into the explanation. Physical geography consequently developed beside related sciences whose approaches overlapped with its own, although their objects of study and preferred methods were not identical.

Within this intellectual setting, a systems approach meant specifying relationships among components and examining how changes were transmitted between them. A catchment could be investigated through the movement and storage of water; a landscape unit through the interaction of terrain, soils and vegetation. The boundary depended on the question being asked. Such reasoning required attention to exchanges beyond the study area and to processes operating at different speeds. It also required a distinction between a spatial association, such as the occurrence of particular vegetation on a slope, and an explanation of how that association had developed and was maintained.

Jaromír Demek's 2008 discussion of geomorphology within landscape ecology illustrates this geographical understanding of relationships. Relief influenced climatic and ecological differentiation through elevation, slope orientation and the organisation of valleys. The land surface also retained evidence of earlier environments and human intervention. His argument connected the shape of the terrain to present processes and to environmental history. A valley therefore had several scientific meanings: it organised movement through the landscape, created contrasts in local conditions and preserved traces of its own development. This

approach sustained a role for geomorphological interpretation within broader environmental research, even as individual investigations became more specialised.

Environmental hazards were already part of the research agenda at the beginning of the independent state. In 1994, Mojmír Hrádek, Jaromír Kolejka and Rostislav Švehlík published a regional assessment of rapid geomorphological hazards in the Czech Republic. Their scope included mass movements, erosion and flooding, alongside other potentially damaging processes. The article demonstrates that an applied concern with environmental risk preceded the major floods that subsequently attracted wider attention. Its regional perspective also mattered. The task was to establish where particular processes could occur and what conditions made them consequential, using knowledge of the country's environmental differentiation.

The transition to new technologies could proceed through landscape synthesis itself. Kateřina Batelková, Kolejka and Jan Pokorný's 1996 study of Horňácko in the White Carpathians combined geographical information systems with an assessment of natural landscape units, described as geosystems. Nine existing or proposed functions were evaluated to identify suitable uses and available territorial reserves. The investigation addressed a region whose economic circumstances had been affected by the nearby state border after Czechoslovakia's dissolution. It brought established geographical reasoning into a new practical setting. The authors nevertheless recognised that favourable natural conditions could not guarantee the implementation of a proposed activity: economic and social assessment remained necessary. Their synthesis supplied an environmental basis for planning while leaving the wider decision open.

The geobiocoenological tradition provided another way of relating environmental differentiation to practical judgement. Buček's account of ecological networks, published in the 2012 special issue of *Ochrana přírody*, explained how geological substrate, relief, soils and climate informed the differentiation of potential ecosystems. This knowledge supported the selection of biocentres and the connections between them within territorial systems of ecological stability. Existing areas of ecological value had to be distinguished from the functioning network that planners wished to create. The distinction made field survey indispensable and prevented a proposed connection on a map from being treated as an already established ecological relationship. Here the systems approach involved an explicit account of spatial connections, environmental conditions and the time required for interventions to become effective.

At the close of the 1990s, Demek also proposed a change in the purpose of geoecological research. Writing in the Slovak *Geografický časopis* in 1999, he argued for greater attention to restoration and the recovery of self-maintaining geosystems after human disturbance. Continuous monitoring and developments in dating, remote sensing and geographical information systems were among the means through which he expected the field to advance. This was a contemporary programme for research, rather than evidence that the proposed transition had already been completed. It placed methodological renewal in the service of a substantive environmental problem: understanding what recovery required and how its course could be assessed.

The availability of digital information introduced difficulties of its own. In 2005, Kolejka examined the problem of combining geographical datasets produced independently at different scales and resolutions. Overlaying thematic layers could create combinations of attributes that did not correspond to the actual landscape. His digital landscape model sought to improve their logical integration as well as their geometric compatibility. The issue reached beyond the handling of files. A procedure could run correctly while its inputs remained environmentally inconsistent. Physical-geographical knowledge therefore had a role in checking whether the assembled database represented relationships that could plausibly exist in the territory being studied.

Kolejka and Jiří Žaloudík's work on landscape monitoring in 2006 extended this concern to change through time. Historical maps and aerial or satellite imagery supplied observations from different periods, while digital methods made their comparison more extensive and detailed. Their examples ranged from the analysis of images acquired at different dates to an integrated digital landscape model incorporating natural and social characteristics. The scientific gain was the ability to examine transformations in their geographical setting. Comparison still required care: a difference between two representations could reflect a change in the landscape, a difference in classification or the properties of the original source. Historical interpretation remained part of the method.

Quantitative classification offered a further route towards synthesis. In 2010, Tomáš Chuman and Dušan Romportl combined eight datasets describing terrain, soils, reconstructed vegetation, climatic conditions and land cover to identify landscape types across the Czech Republic. Their method adapted a classification technique used in vegetation research and linked statistical distinctions to geographical information systems. Diagnostic variables made the basis of the resulting types more explicit. The study also acknowledged the coarseness associated with its national grid and computational constraints. Its achievement lay in making a particular classification procedure open to examination and comparison. The resulting units depended on selected evidence and analytical decisions, which readers could assess rather than simply inherit from a finished map.

National geomorphological mapping similarly acquired new analytical possibilities. Demek, Břetislav Balatka, Karel Kirchner, Peter Mackovčin, Tomáš Pánek and Petr Slavík's 2011 assessment used a digital map prepared for the Landscape Atlas of the Czech Republic. The map combined earlier surveys with interpretation of thematic materials, imagery and field observations, retaining principles developed through international geomorphological mapping. Its database allowed landforms and their attributes to be measured and compared across the country. This was a substantial extension of an established cartographic tradition. Classification by origin and process continued to supply the scientific meaning of the mapped objects, while the digital structure enabled quantitative questions about their distribution and diversity.

These developments did not make all geographical units interchangeable. A region distinguished by its environmental history served a different purpose from a recurring landscape type or an area contributing water to a stream. Each could be appropriate, provided that its definition corresponded to the process or comparison under investigation.

Methodological renewal increased the number of possible spatial representations and made their selection more consequential. Researchers had to explain why a chosen boundary or resolution helped answer the question. Greater numerical precision could otherwise conceal a mismatch between the unit of analysis and the environmental relationship being interpreted.

The interpretation of environmental history became more closely constrained by independent chronological evidence. A 2014 study led by Zbyněk Engel, with Czech, Polish and French participation, investigated the last glaciation in the Krkonoše Mountains. It combined geomorphological evidence with beryllium-10 exposure dating of moraine boulders and Schmidt-hammer measurements, establishing a chronology that could be compared with glacial developments elsewhere in Central Europe. The methodological significance concerned the relationship between observation and time. Landform position and appearance could be tested against measurements bearing on exposure history. Field recognition of the deposits remained essential, because a measured age acquired environmental meaning through the context of the sampled material. International cooperation brought specialised laboratory methods into an investigation rooted in a familiar regional landscape.

Research on extreme events made the relationship between environmental history and present processes particularly urgent. Jakub Langhammer and Vít Vilímek's analysis of the August 2002 flood in the Otava basin, published in 2008, investigated long-term land-use change, drainage and modifications of streams and floodplains. Historical sources, spatial data and field mapping were brought together to assess their geographical distribution. The study found considerable differences between parts of the basin and used a combined analysis of landscape modification, physical conditions and evidence of flood effects. Its approach gave environmental attribution a spatial basis. An alteration documented somewhere within a catchment could not automatically explain damage everywhere within it; the relevant relationships had to be investigated at the places where processes and consequences interacted.

Long observation series created another form of methodological continuity. Established in 1994, the GEOMON network followed the movement of elements into and out of small forested catchments recovering from acidification. Filip Oulehle and colleagues' synthesis in 2021 connected these records with soil and vegetation stores and the main components of the water balance. The accumulated observations documented recovery from atmospheric pollution while also revealing the effects of the drought of 2014–2019. Earlier environmental pressures continued to matter: soils could release stored sulphur after deposition had declined. The network thus supported questions that had changed substantially since its establishment. Its contribution to physical geography and geoecology arose through cooperation across disciplinary boundaries and through the persistence of comparable measurements over time.

The same landscape could consequently contain several overlapping histories. A present measurement might reflect an earlier period of pollution, a recent disturbance and the weather of the observation year. Explaining that measurement required a timescale appropriate to each influence. This strengthened the case for combining investigations of processes with environmental reconstruction. It also complicated the interpretation of recovery. Improvement in one measured property could occur alongside a new source of stress, so the condition of a

landscape could rarely be represented adequately by a single trajectory towards an assumed equilibrium.

Remote sensing became especially useful when connected to observations of environmental functioning. Marian Švik and colleagues' 2020 investigation combined Landsat vegetation-index series with deposition and stream-export data from GEOMON catchments. It examined relationships between forest change and the reduction of acid deposition, using field records to interpret patterns visible from space. Different indices did not provide equivalent information about disturbance and recovery. This work demonstrated the value of linking the spatial reach of satellite observations with measurements of biogeochemical processes. A changing spectral signal became more informative when examined alongside evidence of what entered the ecosystem and what was exported in stream water.

At finer spatial scales, UAV photogrammetry changed the observation of recent geomorphological activity. Langhammer and Tereza Vacková's 2018 study tested a method on the effects of a December 2015 snowmelt flood in the Šumava Mountains. It combined an orthophoto, a digital elevation model and derived information about surface structure to classify flood deposits and bank erosion. Combining two-dimensional imagery with 3D information improved the distinction between features that could appear similar in an image. The study exemplified a shift towards repeatable, detailed documentation of an event's effects. It also showed why the selection of measured properties mattered: the visual appearance of a surface alone did not contain all the information needed to interpret its geomorphological character.

Process modelling supplied a complementary means of investigating relationships that could not be isolated easily in the field. Michal Jenicek and Ondrej Ledvinka's 2020 research examined snow storage, groundwater recharge and streamflow in 59 Czech mountain catchments. Simulations for 1980–2014 were evaluated against observations, and hypothetical scenarios helped separate the contribution of snow from other components of the water balance. The analysis showed how the preceding winter's snowpack could influence summer low flows through its effect on recharge. This gave a precise form to a systems question: conditions in one season affected the response observed in another. The interpretation depended on a model whose representation of storage and transfer was tested against measured behaviour.

Such experiments changed the kinds of explanation physical geographers could attempt. Observations could establish that variables changed together, while a model allowed selected conditions to be altered and their consequences explored. The distinction between those operations remained important. A simulated response was conditional on the model and its inputs; it was not an additional field observation. Used carefully, modelling made assumptions visible and helped identify which measurements would be most useful for distinguishing between explanations. It therefore belonged within an iterative relationship with field research, in which observed discrepancies could lead to a revised representation of the process.

The comparative range of this work had broadened by the end of the period. A 2025 study by Ondrej Hotovy, Ondrej Nedelcev, Jan Seibert and Jenicek examined rain falling on an existing

snowpack across 93 catchments in Czechia, Germany and Switzerland. It used a conceptual hydrological model and combinations of temperature and precipitation perturbations to explore possible changes in runoff. Responses differed between regions, elevations and parts of the cold season. This was a sensitivity experiment, with conclusions conditional on the imposed changes. Its wider significance for Czech physical geography was the use of geographically contrasting catchments to investigate a shared mechanism. Regional differences became evidence through which the explanation could be tested and qualified.

Restoration research supplied a particularly revealing test of integration in 2025. Langhammer, Oleksandr Hordiienko and Veethahavya Kootanoor Sheshadrivasan examined rewetting at the Rokytka mountain peat bog using multispectral and thermal UAV observations together with measurements in the field. Their analysis covered vegetation seasons from 2019 to 2024. Surface water expanded after the installation of dams blocking former drainage channels, but the newly rewetted zones also showed increased surface temperatures. The authors associated the thermal response with vegetation clearance and the design of the dams. The case gave empirical substance to the earlier programme of restoration geoecology: evaluating an intervention required attention to interacting hydrological and microclimatic effects. The expansion of surface water left further questions about the restored system's overall behaviour.

The promise of synthesis remained a matter of debate throughout these changes. In their contribution to the Olomouc geographical conference proceedings in 2010, Kolejka and Kirchner recognised the scientific opportunities offered by modern measurement and analysis while questioning the predominance of narrowly analytical work. They argued that physical geography's ability to relate specialist findings was insufficiently developed and communicated. Their position was an intervention by particular authors, rather than a collective judgement accepted by the discipline. It is nevertheless valuable historical evidence. Methodological renewal was being assessed by Czech physical geographers themselves in terms of the explanations it produced and the uses to which those explanations could be put.

The tension they identified cannot be resolved by requiring every investigation to cover the whole landscape. A precise study of one process may provide evidence without which a wider explanation remains speculative. Synthesis becomes scientifically useful when the connections between findings can be stated and examined. The examples considered here show different ways of doing that, including compatible spatial classifications, comparisons between catchments and measurements of more than one response to an intervention. Their common requirement was an explicit relationship between the question, the evidence and the scale of interpretation. The breadth of physical geography gave it opportunities for such work, while also imposing a demanding standard of explanation.

For international research training, this development offers a practical way of reading the Czech literature. An early geographical assessment can be compared with a later digital or modelling study to establish which questions changed and which assumptions persisted. Attention to the unit of analysis and the source of each measurement helps distinguish a more detailed description from a stronger explanation. The published studies also make visible the

cooperation needed to connect environmental archives, field observations and specialised analysis. Scientific traditions are encountered through the decisions researchers made about evidence and through the problems they considered worth pursuing.

Across 1993–2025, Czech physical geography thus developed through the interaction of accumulated regional knowledge with methods that made environmental relationships more measurable and more open to scrutiny. Its systems approaches took several forms, reflecting differences between classification, process explanation and the evaluation of interventions. Renewal was most convincing where a method allowed an earlier proposition to be tested, a relationship to be traced over a longer period or an unexpected response to be explained. The enduring scientific task was to understand how a particular landscape worked and changed, with sufficient precision to recognise where the explanation needed revision.

Landscape Structure and Transformation: Land Use, Environmental Change and Physical-Geographical Synthesis

The transformation of Czech landscapes after 1993 followed several different courses. Agricultural land gave way to grassland and woodland in some regions, while development around cities converted productive soils into built surfaces. Elsewhere, large cultivated fields remained a conspicuous inheritance of the previous agricultural system. Physical-geographical research increasingly examined how these changes affected the organisation and functioning of the landscape. Its contribution depended on relating the distribution of land uses to terrain and soils, and on establishing what a change in spatial pattern meant for environmental processes. By 2025, the evidence supported a differentiated account in which extensification, development and disturbance could occur alongside one another, sometimes within the same locality.

Land cover describes what occupies the surface; land use concerns the purposes and practices through which it is managed. Landscape structure refers to the spatial arrangement of the elements through which environmental processes operate. Their relative areas describe composition, while their size, shape and connections describe configuration. Two areas with similar proportions of woodland and cultivated land may differ substantially in the placement of those components. A wooded strip following a stream has a different relationship to water movement from an equally extensive patch situated elsewhere. The distinction gives land-use research a physical-geographical purpose beyond the calculation of changing totals. It directs attention towards the position of a change and the connections through which its effects can extend into neighbouring parts of the landscape.

This question was explicit near the beginning of the period. Zdeněk Lipský’s 1994 investigation of an agricultural landscape in Central Bohemia examined the structural legacy of socialist collectivisation. He argued that statistics on the proportions of arable land, grassland and forest could miss alterations in their spatial arrangement. Field amalgamation and the removal of small landscape elements had changed the agricultural mosaic much more profoundly than

the principal land-use categories suggested. The paper established a useful starting point for subsequent research: the countryside inherited in 1993 had already undergone major transformation, and its environmental condition could not be understood from a comparison of land-use areas alone.

The restoration of private ownership did not simply recreate the earlier field pattern. Petr Sklenicka and colleagues' 2014 study of the farmland rental paradox examined how highly fragmented ownership could coexist with large production blocks. Leasing brought numerous small properties into larger operational units. For landscape research, the distinction between the ownership parcel and the field under cultivation was essential. A cadastral boundary could remain legally important without forming a physical division in the landscape. This helped explain why changes in property relations after socialism did not necessarily produce a corresponding recovery of hedges, field margins or smaller cultivated units. The environmental consequences depended on how the land was actually managed and connected.

The research programme associated with Ivan Bičík and colleagues placed the post-1993 period within a longer history of land use. Their 2015 monograph, *Land Use Changes in the Czech Republic 1845–2010*, combined analysis of natural conditions with the investigation of social and institutional drivers. Its LUCC Czechia database included several historical observations, allowing recent change to be compared with earlier periods. Geological conditions, climate and soils entered the explanation of regional farming patterns, alongside markets and policy. This approach gave physical-geographical interpretation a place within a wider study of human interaction with the environment. It also required the compatibility of land-use categories to be examined before differences between dates could be treated as historical change.

Historical cartography supplied a complementary spatial record. Hana Skokanová and a team including Jaromír Demek and Peter Mackovčin published a map-based analysis in 2012 covering land-use development between 1836 and 2006. Nine categories were distinguished from the cartographic sources, including arable land, permanent grassland, woodland and water. Such work allowed the transitions between uses to be located within the landscape. Its importance for the history of Czech research lay in the cumulative reconstruction of change across several generations of maps. The post-socialist years could be studied against a geographically explicit record of earlier transformation, rather than being treated as an isolated episode beginning with a new political system.

The relationship with relief became clearer through regional investigations. Marek Havlíček and Zdeněk Chrudina's 2013 study of Hodonín District used maps spanning the nineteenth century to 2002–2006 to examine land-use change in relation to elevation and slope. Across this long sequence, permanent grassland shifted towards higher and steeper locations, while cultivated and built-up land became more associated with lower, flatter terrain. These were findings for the whole historical sequence, which included observations from 1991 and the early 21st century. They showed how successive decisions could concentrate different uses within different physical settings. Relief supplied enduring constraints and opportunities, while the actual distribution of uses developed through a history of changing demands.

National mapping revealed the contrasting directions of post-socialist change. Lucie Kupková and Bičík's 2016 study distinguished grassing over and afforestation from urbanisation within the period 1990–2010. The contrast was especially clear in their local examples. At Hošťka, near the German border, arable land contracted sharply as pastures expanded; at Jirny, near Prague, agricultural land was converted into residential and commercial development and associated infrastructure. These examples demonstrated why a national decrease in arable land had no single environmental meaning. In one setting it accompanied a less intensive agricultural use, while in another it involved soil sealing. Interpretation required knowledge of the replacement cover, its management and the location of the transition.

The policy context also changed during the period. Kupková, Bičík and Leoš Jeleček's 2021 analysis distinguished the immediate land-use processes from the underlying forces that encouraged them. Their account connected post-1990 change with restitution, altered economic conditions and agricultural support, including the changing incentives associated with European integration. In the historical database they examined, the period 1990–2010 was distinctive for the increase in permanent grassland. This did not imply that policy acted uniformly or independently of natural conditions. The geographical question was how economic incentives and environmental suitability combined in particular regions. That combination helped explain the simultaneous concentration of some activities and withdrawal from others.

The vocabulary of extensification needed equal care. The replacement of cultivation by managed pasture differed from the abandonment of land, even when both reduced the area under arable crops. Subsequent vegetation development depended on continuing management and the conditions of the site. Equally, the conversion of an open area to woodland changed the spatial distribution of habitats and could affect the character of an established cultural landscape. A direction of land-use change therefore provided the beginning of an environmental assessment. Its interpretation required evidence of the resulting conditions and of the functions that researchers or managers wished to maintain.

Later research challenged a simple narrative of continuing decline in land-use intensity. Petra Grešlová, Josef Laštovička, Přemysl Štych and Jan Kabrda's 2023 investigation examined CORINE land-cover changes from 1990 to 2018 alongside measures of material and energy use. Their analysis distinguished the reduction in intensity during the 1990s from a subsequent movement towards greater intensity around and after 2000. It brought the use of biomass into an account previously dominated by the spatial distribution of cover. This widened the meaning of landscape transformation. A field could remain in the same mapped category while its role in production changed, so the apparent stability of land cover could coexist with changes in the demands placed on it.

Urban expansion presented a particularly durable form of conversion. Jana Spilková and Luděk Šefrna's 2010 pilot study of Prague's urban fringe examined the soils appropriated for new retail development. By linking the location of commercial construction to soil quality, their work exposed a cost that could be obscured by treating land primarily as available building space. Productive soil was a geographically differentiated resource, formed under particular environmental conditions and vulnerable to loss through development. The study also

discussed consequences extending beyond agricultural output, including water retention and carbon storage. It brought soil science into an assessment of metropolitan transformation and demonstrated the value of examining the environmental qualities of the land being converted.

The effects of development extended beyond the footprint of buildings. Roads and other barriers could alter connections between remaining habitats. The 2010 volume *Protection of Landscape Connectivity for Large Mammals*, edited by Petr Anděl, Tereza Mináriková and Michal Andreas, combined habitat assessment and modelling with detailed investigation of migration routes. Its treatment of cumulative barriers gave configuration a functional meaning: a route that appeared continuous at a broad map scale could be interrupted locally. The publication was an applied response to fragmentation, bringing ecological requirements into the assessment of spatial development. It also demonstrated that the environmental significance of an element depended on the organisms and movements under consideration, and that proposed connections required examination in the field.

Agricultural research gave independent evidence of the importance of smaller spatial elements. Martin Šálek and colleagues' 2018 comparison of adjacent farming landscapes in South Moravia and Lower Austria examined the relationship between habitat heterogeneity and several groups of organisms. Smaller fields and non-crop elements were associated with higher farmland biodiversity. The cross-border setting allowed researchers to compare intensively cultivated landscapes whose spatial organisation differed because of their development under different political and economic systems. The findings strengthened the case for investigating the internal arrangement of agricultural land. They also connected a long-standing geographical concern with the simplified field mosaic to observations of biological responses, giving the structural analysis a more specific ecological interpretation.

Erosion research established another connection between spatial structure and environmental functioning. A study published in 2019 by Jan Devátý and colleagues from Czech and Austrian institutions reconstructed historical land patterns in Central Bohemia and Lower Austria. It estimated erosion risk under different assumptions about connections between parcels and showed that the organisation of cultivated blocks could substantially affect estimated soil loss even where the total agricultural area changed little. The absolute estimates depended on modelling choices, but the influence of landscape layout remained visible across the comparisons. This was a significant form of synthesis: historical decisions about field structure were connected to terrain, surface flow paths and the movement of soil. It also clarified why an assessment based only on the percentage of land under cultivation could be inadequate.

Direct observations helped specify where such movements occurred. Miroslav Dumbrovský, Karel Drbal, Veronika Sobotková and Jana Uhrová's 2020 study analysed ephemeral gullies measured in South Moravian maize-growing areas during 2012–2017. Their assessment used 51 recorded cases, mainly on deep loess soils, to investigate relationships between gully dimensions and contributing drainage area. The findings supported efforts to locate potential erosion pathways and estimate sediment movement. Within the wider landscape account, this work connected a visible feature in a cultivated field with the area supplying concentrated

runoff. It gave concrete physical content to the proposition that the arrangement of land and its management affected processes extending across individual parcels.

These studies made the boundary of the cultivated field a subject for environmental investigation. A property boundary, a change in crop cover and a break in slope might occupy different positions. Their relationship determined whether an analytical division corresponded to a meaningful interruption in the movement of water or sediment. Physical-geographical synthesis required those distinctions to be made before administrative or agricultural units could be used to explain a process. This was also a reason for linking maps with observations after rainfall. The pattern visible in a database needed to be related to the pathways through which an event actually developed.

Floodplain research revealed similarly long connections between land use and physical alteration. Skokanová's 2008 investigation of the lower Dyje reconstructed the effects of river engineering on the channel, adjoining water bodies and land use. It traced the consequences of earlier regulation, including the loss of connections that sustained cut-off channels and oxbow lakes. It also identified an increase in water-body area and watercourse length in some sections following revitalisation works from the 1990s. These findings situated restoration within a longer sequence of engineering and agricultural change. The floodplain had to be understood through the relationship between channel form, water supply and surrounding uses. An increase in a mapped category such as water area was informative only when the kind of water body and its connections were established.

Mining landscapes presented a more conspicuous reworking of the physical substrate. Their scientific assessment involved questions about the development of habitats on surfaces that had been excavated, deposited or deliberately reshaped. Robert Tropek and colleagues' 2010 research compared technically reclaimed plots with plots undergoing spontaneous succession in limestone quarries in the Bohemian Karst. Total species richness did not differ between the two approaches, but spontaneously restored plots supported more rare species. The addition of topsoil affected the microhabitat conditions associated with reclamation. The study challenged an assessment of recovery based mainly on the rapid establishment of vegetation. Environmental value depended on the resulting habitats and the species they supported, including those adapted to open, sparsely vegetated conditions.

This ecological work contributed to landscape synthesis through its attention to differences within the broad category of restored land. A wooded spoil heap, a quarry floor and a newly created lake represented different environmental developments, even if each followed the end of extraction at a particular site. Research had to distinguish the reconstruction of a productive surface from the conservation of unusual habitats and from the establishment of new recreational uses. The appropriate judgement depended on the purpose of restoration and on evidence of the site's subsequent behaviour. The visual disappearance of a disturbed surface could not, by itself, establish that an earlier environmental system had been recovered.

The closing years of the period also brought rapid change within areas conventionally classified as forest. Prosper Washaya, Roman Modlinger, Daniel Tyšer and Tomáš Hlásny's 2024 analysis mapped disturbance across Czechia between 2016 and 2022 using optical and radar

observations. It identified seven major outbreak centres whose bark-beetle disturbance culminated at different times between 2018 and 2021. In the core disturbance zone, forest fragmentation increased and connections between forest patches declined. These findings exposed a difference between the continuity of land-use designation and the condition of vegetation on the ground. Explaining forested landscapes required attention to disturbance patterns and their interaction with forest composition and environmental stress, alongside the longer history of afforestation.

The significance of heterogeneity itself became more carefully differentiated. Martina Sychrová, Skokanová, Martin Musil and Jan Divíšek's 2024 study examined both the diversity of cover types and their spatial configuration across Czechia since the nineteenth century. The components showed different patterns in relation to elevation, while forest expansion in mountain regions could reduce compositional diversity. Their results warned against treating heterogeneity as one undifferentiated property. An increase in the variety of mapped cover could have a different origin and environmental implication from an increase in the complexity of its arrangement. The work renewed the early concern with landscape structure through measures that allowed its different components to be compared explicitly.

The distinction matters when assessing apparently favourable trends. Increased fragmentation can signal the disruption of a forest habitat, while a finer mosaic of cultivated fields and non-crop elements can provide more varied conditions within farmland. These processes involve different structures and operate at different scales. Their interpretation requires the ecological relationship to be specified, rather than assigning a fixed positive or negative meaning to the index. Taken together, the agricultural and forest investigations show why physical-geographical synthesis must connect a measure of pattern to the particular process or group of organisms through which its significance is being judged.

By 2025, researchers could demonstrate the coexistence of contrasting transformations at national and local scales. Kupková and Zdeněk Boudný's mapping study, published that year, compared national land-registry patterns for 1990–2020 with detailed local reconstructions extending from the early 1990s to 2019 or 2020. Around Prague, commercial and residential development displaced agricultural uses. In Mostecko, continuing extraction and reclamation produced different, overlapping changes; in Valticko, the expansion of vineyards contributed to the contraction of arable land. The peripheral Trutnovsko case showed a further combination of declining mining activity and extensification. Their comparison made clear that a similar statistical movement could represent different transformations of landscape function. The evidence ended around 2020, while its publication in 2025 marked a further stage in the analysis of the independent state's development.

Such comparisons also exposed the limits of summary coefficients of human influence. Forest, grassland and water categories could be grouped to describe a broad tendency, but their environmental properties depended on origin, condition and management. The forest disturbance studies, quarry investigations and floodplain reconstructions supplied information that broad groupings could not contain. A useful synthesis therefore required several kinds of evidence to be read together. National records established the geographical extent of a transition; detailed research helped explain what had changed within it and what

consequences followed. Agreement between the scales was something to investigate, since the categories used at each scale answered different questions.

Over the period 1993–2025, the study of Czech landscape transformation consequently became more attentive to the relationships concealed by aggregate land-use statistics. The structural critique articulated in the early 1990s developed through historical reconstruction, regional comparisons and investigations of environmental responses. Researchers increasingly distinguished changes in land cover from changes in management, and the legal organisation of property from the physical arrangement of fields. These distinctions enabled the landscape to be understood as the material outcome of decisions operating within particular environmental conditions. They also made the explanation of change a shared task across physical geography, landscape ecology and research on human land use.

The most substantial achievement was a more precise account of why Czech landscapes could change in several directions at once. Long-standing terrain and soil differences helped distribute opportunities and constraints, while policy and economic demands altered the uses made of them. Disturbance introduced changes whose timing and extent could differ sharply from gradual land-use transitions. Physical-geographical synthesis joined these histories through the examination of actual relationships: between field structure and soil movement, between channels and floodplains, and between habitat arrangement and the movement of organisms. Its value lay in explaining the environmental meaning of a transformation at the scale where its consequences became observable.

Biogeography, Soil Geography and Geoecology: Spatial Relationships within Natural Systems

A woodland, a meadow and a spring-fed wetland may lie within a few kilometres of one another, yet belong to markedly different ecological worlds. Their differences emerge through the interaction of geological substrate, soil development, water movement, local climate and the histories of the organisms that inhabit them. Understanding these relationships has remained a central concern of Czech biogeography, soil geography and geoecology throughout the period from 1993 to 2025. Each field approaches the natural environment from a particular direction: biogeography investigates the distribution of organisms and communities; soil geography examines the differentiation of the soil cover; and geoecology considers how living and non-living components operate together within spatially organised systems.

The establishment of the independent Czech Republic provided a new national framework for these investigations, while their intellectual foundations extended considerably further into the past. Botanical surveys, forest typology, soil mapping and the study of regional natural conditions had already produced substantial bodies of knowledge. After 1993, an important scientific task was to bring these inherited materials into forms that supported comparison, quantitative analysis and wider circulation. The resulting development combined the revision of established classifications with new field investigations and the gradual construction of

digital research infrastructures. Its chronology therefore concerns both the production of new observations and the changing scientific uses of observations recorded decades earlier.

One influential source of continuity was the Czech geobiocoenological tradition associated with Alois Zlatník and developed subsequently by Antonín Buček and Jan Lacina. Its central concern was the relationship between a biological community and the environmental conditions of its site. Buček and Lacina's *Geobiocenologie II*, issued in a second edition in 2007, gave this approach a systematic treatment through the ecological typology of Czech landscapes. Altitudinal differentiation, soil nutrient conditions and moisture regimes provided complementary dimensions through which natural systems could be compared. This vocabulary encouraged researchers and students to interpret a vegetation community through its place within a wider environmental complex.

The distinction between potential natural conditions and the vegetation actually present was particularly significant within this tradition. A plantation, an agricultural field or a secondary grassland could be examined in relation to the ecological conditions of its site, even where its present composition reflected extensive management. Potential vegetation supplied a reference model whose interpretation required knowledge of soils, relief and climate. Its value depended on the explicit assumptions under which it was constructed. As environmental conditions changed, the relationship between such reference models and contemporary observations became a continuing scientific question.

Regional biogeography offered another means of assembling these relationships. The 2013 monograph *Biogeografické regiony České republiky*, by Martin Culek, Vít Grulich, Zdeněk Laštůvka and Jan Divíšek, presented detailed accounts of four biogeographical subprovinces and 91 bioregions. Its descriptions brought geology, landforms, soils and climate together with flora, fauna, potential vegetation and the contemporary landscape. The accompanying map at a scale of 1:500,000 placed these accounts within a common national framework. The work's scientific importance lay in the connections established between these categories: regional distinctiveness emerged from their combination, rather than from the distribution of any single environmental attribute.

Such regional syntheses also clarified the different questions that could be asked of geographical space. A bioregion expresses the individuality of a territory through its characteristic assemblage of natural conditions and organisms. An ecological type identifies conditions that may recur in several territories. These approaches support different forms of comparison, and their relationship is particularly useful in a country where substantial ecological variation occurs over comparatively short distances. A regional boundary can organise knowledge and guide investigation, while field measurements reveal the transitions, local exceptions and internal heterogeneity that any small-scale map necessarily simplifies.

During the 1990s and early 2000s, vegetation databases substantially enlarged the possibilities for investigating these patterns. The Czech National Phytosociological Database was established in 1996, with its central collection at Masaryk University in Brno. Milan Chytrý and Marie Rafajová's account, published in 2003, reported 54,310 vegetation plots assembled by November 2002, representing observations collected between 1922 and 2002. Bringing these

records together made it possible to examine plant communities across regions, environmental gradients and periods of research. The authors also documented uneven geographical coverage and preferential sampling of botanically attractive habitats. The database thus preserved the achievements of earlier fieldwork while making the spatial limitations of that inheritance more visible.

A vegetation plot records the coexistence of species within a defined area, usually with estimates of their abundance or cover. Its scientific possibilities differ from those of a record showing that a particular species occurred somewhere within a district or mapping square. Plot data support the comparison of communities and their environmental associations; distribution records support questions concerning geographical ranges and regional species pools. The development of Czech ecological research increasingly depended on maintaining these distinctions while finding ways to analyse the different forms of evidence together.

A clear example of methodological renewal appeared in David Zelený and Milan Chytrý's 2007 investigation of vegetation in the deep valleys of the Vltava and Dyje. Their study connected vegetation observations with topographic and soil measurements along slopes descending towards the valley floor. Statistical analyses identified environmental gradients involving moisture, nutrients, soil reaction, light and temperature-related conditions. Soil variables were slightly stronger predictors of vegetation composition than topographic variables, although both contributed information. The influence of slope aspect also varied with position above the valley bottom. These findings gave quantitative expression to a long-standing Czech interest in the ecological distinctiveness of deeply incised river valleys, while demonstrating that the relationship between landform and vegetation changed within the valley itself.

Research on spring fens provided an equally instructive meeting place between biogeography, hydrology and soil science. Michal Hájek, Petr Hekera and Petra Hájková's 2002 study of the Western Carpathian flysch zone compared vegetation types along a gradient from mineral-poor to mineral-rich conditions. Water calcium and magnesium concentrations, pH, conductivity and soil organic carbon were among the properties most closely associated with the principal vegetation gradient. The study also showed that tufa formation depended on the wider chemical composition of springwater and on climatic and topographic conditions. Across the Moravian–Slovak borderland, a wetland's ecological character could therefore be understood through the movement and chemistry of water entering a particular site.

Environmental measurements, however, left further questions concerning the geographical composition of these communities. In 2007, Michal Horsák, Michal Hájek, Daniel Dítě and Lubomír Tichý compared snail assemblages and vegetation in Western Carpathian spring fens in Czechia and Slovakia. Their analysis identified a pronounced geographical differentiation across a relatively small territory, which persisted after accounting for important aspects of water chemistry. Historical development was proposed as a major influence on the modern pattern, particularly for organisms with limited migration rates. The study extended the explanation of spatial relationships beyond present habitat conditions to include the formation of regional species pools and the histories of dispersal and survival.

The relationship between contemporary environment and historical inheritance is fundamental to the interpretation of natural systems. Suitable conditions do not guarantee that every potentially compatible species will occur at a site. Colonisation requires access, while persistence depends on the continuity of favourable conditions and the capacity of populations to survive disturbance. Conversely, a community may retain evidence of an earlier ecological setting. Czech investigations of valleys and fens illustrate how the geographical explanation of biodiversity becomes more precise when environmental gradients are considered alongside the temporal development of the organisms occupying them.

Within soil geography, the period after 1993 involved a comparable effort to connect inherited survey knowledge with a more coherent analytical framework. The Czech taxonomic soil classification system, published in book form in 2001, drew upon earlier morphogenetic classifications and developments in forest soil classification. Cooperation between agricultural and forest pedologists was especially consequential because these fields had accumulated information through partly separate survey programmes. A shared classification supported the comparison of soils across land uses and improved the correspondence between their maps. Its continuing comparison with international systems also provided a means of communicating Czech soil knowledge within a broader scientific setting.

Classification gives soil geography a common descriptive language, but its geographical purpose extends to explaining how soils are arranged and why their properties vary. A soil profile develops through processes operating at a particular location, while receiving water, dissolved substances and sediment from its surroundings. Its characteristics may therefore reflect both local formation and connections with neighbouring parts of the landscape. The spatial arrangement of soil horizons, drainage conditions and parent materials provides evidence through which these relationships can be investigated. This perspective connects the examination of an individual profile with the interpretation of slopes, catchments and regions.

Jan Němeček and Josef Kozák's 2003 work on a national soil map at a scale of 1:250,000 illustrates this connecting role. Their application of the SOTER approach linked soil information with terrain and parent materials, drawing upon an existing digitised soil map. They adapted the procedure to Czech conditions rather than applying a uniform hierarchy of landform, lithology and soil associations throughout the country. In landscapes with deep sedimentary cover, the prevailing soil mosaic and its parent materials were important in defining mapping units. The study demonstrated that the relationship between relief and soils required interpretation appropriate to the geological setting. Its digital layers also established a practical basis for comparing soil patterns with other environmental information.

The expansion of terrain modelling subsequently allowed researchers to test how well measurable landform attributes could predict particular soil properties. In 2006, Vít Penížek and Luboš Borůvka compared methods of predicting soil depth using elevation, slope and aspect as additional information. Their assessment employed independent validation data and showed that terrain information improved prediction, although the improvement was relatively modest because the correlations were weak. The significance of this result lay partly in its restraint. The availability of a digital elevation model increased analytical possibilities, while

validation established how much explanatory value its variables actually contributed to the soil property under investigation.

Spatial soil research also addressed chemical conditions within forest ecosystems. Luboš Borůvka, Lenka Mládková and Ondřej Drábek's 2005 investigation of the Jizera Mountains examined soil acidification and different forms of aluminium in surface organic and subsurface mineral horizons. The study connected chemical measurements with the distribution of site conditions. Differentiating between soil horizons and aluminium fractions enabled a more specific account of environmental variation than a general description of a mountain region as acidified. For geoecology, this approach was valuable because it related the chemical environment experienced by organisms to the spatial organisation of the soil system.

The geographical distribution of soils could also preserve evidence of material transferred through a landscape. Tereza Zádorová, Daniel Žížala, Vít Penížek and Šárka Čejková examined colluvial soils in a Central Bohemian Luvisol sub-catchment in 2014. Their combination of detailed field survey, soil analyses and terrain modelling identified relationships between depositional soils, topographic derivatives and soil organic carbon. The topographic wetness index was the most suitable terrain predictor among those assessed. The study showed how the contemporary soil cover incorporated the redistribution of material between slope positions. A soil map could consequently be read as an account of connected processes, with differences between profiles recording both formation in place and the arrival of material from elsewhere.

By the end of the period, national-scale reassessment continued to reveal the value of older soil observations. Jessica Reyes Rojas and colleagues' 2025 study of Czech chernozemic soils examined their properties, classification and environmental controls using legacy data. Among its findings, parent material was more influential than the climatic and terrain variables considered in explaining soil organic carbon content within the analysed dataset. The authors also evaluated correspondence with the 2022 World Reference Base for Soil Resources. This combination of historical observations, contemporary classification and environmental analysis demonstrated how established soil categories could be investigated afresh. The result concerned a defined group of soils and a particular set of properties, with its geographical interpretation depending on that scope.

Biogeographical research underwent a related expansion through the integration of species occurrence information. The PLADIAS Centre of Excellence, operating in 2014–2018, addressed the fragmentation of Czech botanical data among separate collections. Jan Wild and colleagues' 2019 account of the Pladias occurrence module described the integration of more than 13 million records from national databases, regional projects and new contributions. Record validation and the assessment of geographical and taxonomic coverage were central parts of the work. This made a broad botanical inheritance more accessible to spatial analysis, while retaining expert evaluation as an essential condition of reliable mapping.

A complementary development involved assigning ecological meaning to species records. In 2018, Milan Chytrý, Lubomír Tichý, Pavel Dřevojan, Jiří Sádlo and David Zelený published revised Ellenberg-type indicator values for the Czech flora. These described species'

relationships with light, temperature, moisture, soil reaction, nutrient availability and salinity. The values drew upon field knowledge, literature and analyses of co-occurrence, and were tested against measured environmental variables. For geographical research, they offered a consistent way to compare the environmental affinities of assemblages. Their interpretation nevertheless required attention to the difference between a biological indication of site conditions and a direct physical or chemical measurement.

The possibilities and difficulties of large botanical databases were brought together in Barbora Klímová and colleagues' 2025 study of species richness across Czechia. Using Pladias, the authors examined current environmental conditions, landscape structure and historical landscape development, while comparing methods of accounting for uneven sampling intensity. Carbonate bedrock and climatic moisture were prominent influences on the richness of several species groups, while the long-term continuity of forests and grasslands also contributed. The study showed that sampling intensity could distort apparent environmental relationships. It therefore advanced a substantive explanation of plant diversity alongside a methodological assessment of how confidently that explanation could be drawn from the available records.

Soil information systems were developing in a similar direction. Adéla Marie Marhoul and colleagues' 2025 description of a new version of PUGIS connected database design with applications involving soil bulk density and organic carbon. Much of the underlying agricultural soil information originated in the systematic survey conducted in 1961–1970, with forest soil databases supplying another component. The history of Czech soil geography thus included an extended process of recovering and reusing information created for earlier purposes. The scientific value of such reuse depended on understanding the original measurements and classifications, and on making their relationships explicit within the information system.

Pladias and PUGIS illustrate complementary responses to a shared research problem. Both fields possessed extensive observational archives whose scientific possibilities exceeded their original formats. Integration allowed researchers to ask questions across larger territories and to compare observations through common analytical procedures. It also increased the importance of provenance, geographical accuracy, measurement conventions and the treatment of missing information. A record's usefulness depended on knowing how it had been produced and what it could reasonably represent. The digital transformation of these disciplines therefore involved substantial work on the meaning and comparability of data.

Across the three fields, the development from 1993 to 2025 can be interpreted through a gradual widening of analytical connections. The 1990s and early 2000s saw important work on organising vegetation records, maintaining ecological typologies and harmonising soil classifications. During the following decade, quantitative investigations increasingly tested relationships between organisms, soils and terrain within carefully defined study areas. From the mid-2010s onwards, integrated databases and larger comparative analyses expanded the geographical scope of research. These developments overlapped: field description, classification, laboratory measurement and statistical modelling continued to depend upon one another.

The institutional setting of this work also crossed disciplinary boundaries. The selected studies involved university departments of botany, zoology, geography and soil science, alongside Academy research and specialised environmental institutions. Their common questions concerned spatial relationships that exceeded the usual responsibilities of any one department. Vegetation research required geological and soil information; soil mapping drew upon terrain analysis; and the interpretation of species distributions required ecological, historical and geographical knowledge. Geoecology provided a useful meeting ground for these contributions because it focused attention on the organisation of the natural system being investigated.

Scale remained a decisive consideration. A relationship identified within a spring fen cannot automatically explain a national pattern of species richness, while a national map may conceal the soil and moisture contrasts controlling a community on an individual slope. Research design therefore required a clear statement of the spatial unit under examination and the processes expected to operate within it. The same care applied to time. Contemporary environmental measurements, historical vegetation plots and soil observations from an earlier survey describe different aspects of a system whose components change at different rates.

By 2025, Czech biogeography, soil geography and geoecology offered a substantial body of research through which these relationships could be examined together. Their development rested on the continuing interaction between detailed knowledge of particular places and methods capable of comparison across places. Regional monographs preserved environmental context; field investigations tested mechanisms; and digital infrastructures supported new questions about distribution, diversity and ecological conditions. Their combined contribution was a more discriminating understanding of natural spatial order, including the local variations, historical inheritances and observational uncertainties through which that order becomes scientifically intelligible.

Czech Physical Geography beyond National Borders: Polar Regions, High Mountains and International Field Research

Between 1993 and 2025, Czech physical geography developed a substantial field of activity beyond the territory of the Czech Republic. Research in Antarctica, the Arctic and high mountain regions opened direct access to contemporary glaciers and extensive permafrost, while extending investigations of slope processes into markedly different environmental settings. These investigations widened the empirical foundations of the discipline. They also changed the organisation of research, as individual expeditions became connected with permanent facilities, repeated measurements and international programmes. Their scientific importance is best understood through the questions they made possible, the observations they sustained and the relationships established with researchers in the countries and regions concerned.

International work was already part of the discipline's reorientation during the 1990s. Jan Kalvoda's 2001 review of physical geography at Charles University documented research undertaken by staff and doctoral students in other parts of Europe, the Americas, Asia and Africa. Its account of projects in 1997–2001 included mountain environmental change, cooperation on erosion and glacial chronology, and investigations of hazardous processes in Peru's Cordillera Blanca. The review placed these activities within an approach connecting measurements of present processes with the longer history of landform development. It provides contemporary evidence that foreign fieldwork formed part of a wider programme of explanation and comparison during the first decade of Czech statehood.

The international volume *Geomorphological Hazards in High Mountain Areas*, edited by Jan Kalvoda and Charles L. Rosenfeld in 1998, offers another indication of this orientation. Contributions examined glacial floods, slope movements and related environmental problems across mountain regions. Czech participation included Kalvoda's work on the High Tatras and a chapter by Vít Vilímek and the Peruvian specialist Marco Zapata Luyo on the Cordillera Blanca fault zone. Through such collaborations, the interpretation of mountain hazards was connected with knowledge of tectonic activity and Quaternary landscape development. The volume also shows how Czech researchers participated in assembling comparative knowledge, alongside conducting investigations at particular sites.

Polar geography followed a related course through cooperation with established foreign stations. Masaryk University's geographical research tradition in the polar regions predated 1993, but a new Antarctic phase began in 1994. Its researchers worked at the Polish Henryk Arctowski and Peruvian Machu Picchu stations on King George Island, with further investigations around Ukraine's Akademik Vernadsky station on Galindez Island. These arrangements provided access to environments and logistical experience that could support subsequent work. They also locate the origins of the later Czech Antarctic programme within an existing international scientific community. A national facility would emerge from relationships and experience accumulated through these earlier collaborations.

The construction of the Johann Gregor Mendel station on James Ross Island gave this work a more durable geographical centre. Masaryk University built the station in 2004–2006, following preparations that had begun in the 1990s; its formal opening took place on 22 February 2007. The distinction between construction and inauguration explains the different dates associated with its establishment. Located near the Antarctic Peninsula, the station supported repeated summer expeditions to an area containing substantial ice-free terrain. For physical geography, this setting offered opportunities to investigate relationships between climate, glacier change and the processes operating on exposed ground. The station's significance lay in the research continuity that its accommodation, equipment and logistical support could sustain.

Continuity altered the kinds of questions that fieldworkers could address. A single visit might document landforms or describe conditions during one summer. Returning to the same locations allowed researchers to examine variability between years and to test whether a conspicuous event belonged to a longer change. The scientific unit of observation could therefore extend beyond an expedition to a sequence of measurements whose comparability had to be maintained. Instrument locations, measurement procedures and the circumstances

of interruptions became part of the evidence. In this respect, the development of polar infrastructure changed both the practical conditions of research and its temporal reach.

The establishment of a Circumpolar Active Layer Monitoring–South site near the Mendel station in February 2014 illustrates this development. Filip Hrbáček and colleagues' 2017 study examined the seasonally thawed ground above permafrost, known as the active layer, through temperature profiles and mechanical probing. The monitoring grid crossed a Holocene marine terrace and Cretaceous sedimentary material. Differences in these substrates affected the observed depth of thaw and the thermal behaviour of the ground. The study connected a standardised international monitoring approach with detailed knowledge of local geology. It showed why a regional description of Antarctic cold conditions required investigation of the ground's spatial heterogeneity.

By 2025, the same monitoring setting supported an assessment extending across the seasons 2013/14–2022/23. Hrbáček, Michaela Kňažková, Kamil Láska and Lucia Kaplan Pastíriková reported warming and thickening of the active layer. Thickness determined from the zero-degree isotherm increased by an average of 1.5 centimetres per year during the study period, while mechanically probed thaw depths increased by 1.9 centimetres per year. Lithological differences remained pronounced. These results demonstrate the value of preserving observations through successive field seasons, while the different measurement definitions explain why the two reported rates need to be distinguished. They describe change at a particular monitoring site over a specified interval.

Glacier monitoring provided another example of the scientific value of repeated access. In 2024, Zbyněk Engel, Kamil Láska, Jana Smolíková and Jan Kavan analysed measurements from Lookalike Glacier and Davies Dome on James Ross Island. Monitoring begun in 2009 revealed a broadly balanced mass budget during 2009/10–2014/15, followed by mass loss during the subsequent period examined, ending in 2020/21. The authors associated the transition with changing air temperature conditions. Such a record made it possible to identify a change between successive phases within a relatively short observational history. It also placed measurements of individual glaciers within the wider problem of how small Antarctic glaciers respond to variations in their climatic environment.

These investigations brought together institutions whose contributions overlapped in the field. The glacier study involved Charles University, Masaryk University and the University of South Bohemia. Shared research locations enabled expertise in geomorphology, climatology and glaciology to meet around common measurements. The resulting publications should therefore be understood as products of cooperating teams. Their Czech institutional base was significant, while their questions concerned processes whose relevance extended well beyond a national research system. This combination of responsibility for particular observations and participation in wider explanation became a characteristic feature of the work.

In the Arctic, the University of South Bohemia developed a complementary infrastructure on Svalbard. Josef Elster's 2016 account records the opening of Julius Payer House in Longyearbyen in 2013 and of the Nostoc field camp at Petuniabukta in 2015. The construction programme for the Josef Svoboda research infrastructure was completed in 2015, with the

vessel Clione prepared for regular operation around Svalbard. These facilities connected access through a settlement with work at a more remote field location. Their research remit included climatology, glaciology, geomorphology, hydrology and limnology alongside biological sciences. The arrangement supported an investigation of polar environments in which physical conditions and ecological processes could be studied within the same regional setting.

Climatological measurements at Petuniabukta had already demonstrated the importance of local geographical controls. Kamil Láska, Denisa Witoszová and Pavel Prošek's 2012 paper examined observations from 2008–2010, including solar radiation, air and surface temperature, humidity and wind. The study related variability to atmospheric circulation, the surrounding terrain and conditions in the fjord. Temperature differences between Petuniabukta and the station at Svalbard Airport were affected by contrasting sea-ice conditions during winter and spring. The findings gave substance to a geographical principle with broad application: observations from a nearby station require careful interpretation when transferred across different surfaces and topographic settings.

Later Svalbard research also connected glacier behaviour with rapid changes beyond the ice margin. Jan Kavan and an international team's 2024 study examined the surge of Recherchebreen and the subsequent formation of a delta. Following an advance of approximately 1,200 metres from 2018, the glacier slowed abruptly in June 2020. A delta then extended roughly 450 metres in less than two months. The authors interpreted the close timing as evidence of the release of water and sediment stored beneath the glacier during a reorganisation of drainage. Combining satellite observations with field documentation, the study showed how a short episode of glacier dynamics could leave a substantial coastal landform.

The Antarctic and Svalbard examples expanded Czech expertise across contrasting polar environments. They also encouraged research at the boundaries between established specialisations. A glacier supplies water and sediment to systems downstream; thawing ground modifies the conditions through which water moves; and local climate depends partly on the surfaces exchanging heat and moisture with the atmosphere. Field programmes capable of observing several parts of these relationships offered opportunities for physical-geographical synthesis. Their usefulness depended on measurements appropriate to each process and on an explicit account of how the separate observations could be connected.

High mountain research developed another sustained field of international activity, particularly in the Peruvian Andes. The Cordillera Blanca offered a setting where glacier retreat, unstable slopes and lakes were closely connected with inhabited valleys. The scientific task involved reconstructing changes in mountain systems and identifying the processes through which a disturbance could travel downstream. Cooperation with Peruvian specialists was fundamental to this work, as illustrated by jointly authored studies involving personnel from the national water and glaciological services. Such partnerships connected external scientific methods with regional observations and an established history of investigating glacier-related hazards.

Vít Vilímek and colleagues' 2005 study of Lake Palcacocha combined field investigations and hydrodynamic tests with satellite images and aerial photographs. The authors examined the permeability of moraine material, seepage and changes associated with the retreating glacier. They identified increasing lake volume and the unloading of slope toes as processes relevant to the evolution of potential hazards. The study treated the lake, its natural dam and adjacent slopes as a connected system. Its importance for the development of Czech physical geography lay in this combination of direct observation, historical reconstruction and an applied question concerning environmental change in a specific mountain valley.

Research at Huascaran further demonstrated the continuing role of detailed geomorphological mapping. Jan Klimeš, Vít Vilímek and Marek Omelka's 2009 paper distinguished glacial deposits, historical rock-debris avalanche deposits and material from a prehistoric avalanche. Rock-hardness measurements helped discriminate some deposits but had limited value in separating much older materials. Field mapping proved essential for identifying the prehistoric avalanche's extent. The revised interpretation implied a larger volume or greater mobility than previously recognised. This was a methodological lesson as well as a regional finding: the suitability of an analytical technique had to be tested against the geological history and materials encountered on the ground.

During the 2010s, investigations of individual objects increasingly supported methods for wider comparison. Adam Emmer and Vít Vilímek's 2014 approach assessed the susceptibility of glacial lakes to outburst floods through seventeen characteristics and five separate scenarios. These addressed different possibilities involving slope movements, flood waves from upstream lakes and earthquakes. The procedure combined information from remotely sensed images and terrain data with explicit calculations and decision trees. Testing against lakes with and without recorded outbursts provided a means of assessing its performance. The separate scenarios retained distinctions between mechanisms that a single overall score could obscure, making the method's assumptions and interpretation easier to examine.

An inventory published by Emmer, Klimeš, Martin Mergili, Vilímek and Alejo Cochachin in 2016 extended the analysis across the Cordillera Blanca. The team identified and classified 882 lakes using high-resolution imagery, with field surveys providing verification. Historical aerial photographs allowed selected changes to be examined over 1948–2013. The work documented differences between dam types and the persistence of some lakes after their catchments had become deglaciated. It also assessed outburst susceptibility for the large lakes in the inventory. Regional coverage thus became a basis for comparing evolutionary pathways and for identifying where closer monitoring or more detailed investigation was warranted.

A further synthesis in 2020, led by Emmer with researchers based in several countries, examined lake evolution during 1948–2017 alongside the regional record of outburst floods. Lake numbers and total area had increased, while the historical peak in recorded outburst frequency occurred between the late 1930s and early 1950s. The analysis also distinguished the growing importance of bedrock-dammed lakes from the earlier prominence of moraine-dammed lakes. These findings made the explanation of changing hazards more specific. The relationship between deglaciation and flooding depended on the evolving arrangement of

glaciers, lakes and potential triggers, including the stage reached by individual lakes within their development.

The 2024 volume *Geoenvironmental Changes in the Cordillera Blanca, Peru*, edited by Vít Vilímek, Bryan G. Mark and Adam Emmer, reflected the breadth attained by this research. Its contents connected geology and geomorphology with climate, hydrology, lakes and glaciation, while also examining hazards and human relationships with the changing environment. Czech contributions appeared within a collective regional account assembled with international specialists. The book represented a form of scientific consolidation in which detailed investigations could be interpreted against a wider environmental setting. It also made visible the connections between physical geography and questions concerning the use of water and the consequences of hazardous events for communities.

In the Nepal Himalaya, long-standing field knowledge continued to acquire new analytical uses. Jan Kalvoda and Adam Emmer's 2021 study of the Makalu Barun region combined repeated field observations and photographic documentation with satellite imagery and terrain information. The field inheritance included expeditions undertaken between 1971 and 2006, while the analysis addressed subsequent environmental conditions through remotely sensed evidence. Four principal morphoclimatic zones were distinguished, ranging from extreme glacial environments to seasonally cold or warm humid valleys. The authors examined the dominant processes within these zones and the transfer of material between them. This provided a spatial framework for investigating how environmental change affected different parts of a very large vertical landscape.

The Himalayan example shows why the history of a research programme cannot be reduced to the dates of its most recent expeditions. Earlier observations can become reference points when later imagery reveals changes in glaciers, slopes or vegetation boundaries. Their value depends on the precision with which locations and conditions were documented. At the same time, combining evidence collected by different methods introduces questions concerning resolution, coverage and comparability. The development of research therefore includes the interpretation of its own observational inheritance, with older field knowledge supplying context for measurements that became technically possible much later.

The Nature of Geomorphological Hazards in the Nepal Himalaya, edited by Jan Kalvoda and Eva Novotná in 2024, placed these investigations within a broader regional synthesis. Alongside landform evolution and glacial lakes, its chapters addressed historical cartography, perceptions of hazards and the relationship between natural conditions and settlement. Contributions also explored connections with geodesy through the interpretation of an Earth gravity model. The range of subjects illustrates a physical geography willing to draw upon several kinds of evidence when explaining mountain systems. International contributors and regionally informed studies supported a treatment extending from the physical conditions of hazardous processes to their significance for people living within those environments.

Across these programmes, field research and remote sensing developed through a close working relationship. Images supplied geographical coverage and opportunities to examine change between dates; field measurements helped establish the nature of the surfaces,

materials and processes represented. Their combination required decisions about what could be compared and where direct verification was possible. The selected studies also show that methodological progress sometimes consisted of demonstrating the limits of an available technique. An improved explanation could follow from choosing the appropriate evidence for a particular question, even when that evidence depended on careful mapping or the maintenance of an established measurement series.

International fieldwork also created a demanding setting for the training of researchers. Participation required familiarity with instruments and sampling procedures, but also the judgement to recognise when weather, access or local conditions constrained an observation. The return to a shared site placed each new cohort within an existing scientific responsibility: records had to remain usable by colleagues who would work there later. Masaryk University's polar research group explicitly connected student work on Antarctic samples and data with opportunities for doctoral field research. The wider educational value of such arrangements lay in joining analytical training with an understanding of how environmental evidence is produced under practical constraints.

By the closing years of the period, this international engagement had also acquired clearer representation within specialist scientific networks. The International Permafrost Association approved Czechia's application in 2024, with membership beginning in 2025. The application brought together researchers from Masaryk University, the University of South Bohemia, Charles University and Academy institutes. The association's announcement recognised work extending from monitoring ground thermal conditions to periglacial geomorphology and ecology. Membership provided a formal expression of a research community already connected through field sites and collaborative projects. It should be read alongside the accumulated observations and publications that gave the community its scientific substance.

Czech physical geography beyond national borders thus became a field in which responsibility for particular sites could sustain questions of wider scientific relevance. Measurements on James Ross Island, investigations on Svalbard and collaborative studies in the Andes and Himalaya each contributed evidence grounded in a distinctive environment. Their broader contribution emerged through comparison and through an increasingly careful treatment of how climate, geological conditions and process histories interacted. By 2025, these programmes demonstrated how a research community based in a small Central European country could participate in explaining environmental change across distant regions through sustained observation and international cooperation.

Major Achievements, Research Schools, Leading Scholars and Landmark Publications in Physical Geography

The major achievements of Czech physical geography between 1993 and 2025 can be recognised in the explanations, records and reference works that subsequent researchers were able to use. Regional knowledge became more accessible through revised classifications

and national syntheses. Environmental histories acquired firmer chronologies, while experiments and models tested mechanisms that field description alone could leave uncertain. These developments drew upon established traditions and the work of new research groups. Their significance becomes clearest when individual scholars are considered alongside the collaborative practices and publications through which their contributions entered the wider discipline.

A research school is sustained through shared questions, methods and standards of evidence. Its members may work in several institutions, and its influence may continue through a publication or a field site after its original organisational setting has changed. Czech physical geography during this period displayed this dispersed character. Prague, Brno and Ostrava supported distinctive concentrations of work, with important contributions from Olomouc and other centres. Cooperation among universities, Academy institutes and specialised scientific services frequently crossed these geographical divisions. The resulting schools are best understood as connected intellectual communities whose boundaries changed as their research questions developed.

Jaromír Demek's continuing contribution to regional geomorphology is particularly visible in *Hory a nížiny: Zeměpisný lexikon ČR*, edited with Peter Mackovčin in 2006. The collective work brought together the hierarchy of Czech geomorphological units with descriptions of their relief, geological setting and contemporary landscape. Contributors included Břetislav Balatka, Antonín Buček, Martin Culek, Karel Kirchner and Tomáš Pánek, among others. Its significance extended beyond assembling information about individual territories. The lexicon provided a common geographical vocabulary through which field observations, regional comparisons and environmental assessments could be related. It also placed scholars from different generations within a shared act of synthesis, demonstrating the continuing usefulness of regional expertise after 1993.

At Charles University, Jan Kalvoda articulated an approach connecting physical geography with the wider Earth sciences. His 2001 review, Progress in physical geography, emphasised measurements, mathematical and physical methods, and the interpretation of natural systems across different spatial and temporal scales. It situated studies of contemporary processes alongside evidence of longer environmental development. The review is valuable as a statement of scientific direction during the first post-socialist decade. Kalvoda's contribution included maintaining a place for synthesis within an increasingly specialised research environment: explanations of particular processes were expected to contribute to a wider understanding of landscape evolution and natural hazards.

An important later expression of this collective regional tradition was *Landscapes and Landforms of the Czech Republic*, edited by Tomáš Pánek and Jan Hradecký in 2016. Both editors were based at the University of Ostrava. Published in the *World Geomorphological Landscapes* series, the volume connected an account of the country's geological and environmental setting with studies of particular landscapes and landforms. Its chapters assembled work from a broad community, including specialists in karst, sandstone terrain, volcanic landscapes and mountain relief. The publication made regionally grounded Czech knowledge available within an international comparative framework. Its editorial achievement

lay in giving local investigations a coherent place within an account of the country's geomorphological diversity.

The Ostrava concentration of research also became visible through methodological contributions concerning the timing of slope movements. Pánek's 2015 review, Recent progress in landslide dating: A global overview, examined a worldwide collection of dated landslides and assessed developments in chronological techniques. Particular attention was given to the growing use of exposure dating and the combination of several methods. The review addressed problems encountered far beyond the regions in which Czech fieldwork was concentrated. It helped frame the relationship between an individual date, a sequence of slope movements and the environmental conditions proposed to explain that sequence.

Karel Šilhán's 2021 review of the dendrogeomorphology of different landslide types illustrates a complementary strand of work at Ostrava. Dendrogeomorphology uses disturbances recorded in tree growth to investigate geomorphological events. Šilhán examined how the extraction and interpretation of such signals depended on the type of landslide, its material and its movement mechanism. His review brought together methodological choices, sampling questions and the limits of the resulting chronologies. Tree rings offered detailed temporal evidence, but the interpretation depended on establishing what a particular growth disturbance represented. This attention to the relationship between biological response and physical process connected geomorphology with ecological knowledge.

Experimental research supplied another form of achievement. In 2014, Jiří Bruthans and colleagues published Sandstone landforms shaped by negative feedback between stress and erosion in *Nature Geoscience*. The team included Michal Filippi and other specialists from Czech university and Academy workplaces, alongside international participation. Field observations were combined with physical experiments and numerical modelling to examine how loading affected the resistance of sandstone material to erosion. The proposed feedback explained how the removal of weakly loaded material could leave a more resistant load-bearing structure. Its importance lay in a mechanism that could be investigated experimentally and related to natural arches, pillars and pedestal rocks. The work also demonstrated how questions central to physical geography benefited from cooperation with hydrogeology, rock mechanics and material modelling.

These geomorphological contributions addressed different parts of a common explanatory problem. Regional synthesis established the spatial setting of landforms; dating investigated when changes had occurred; and experiments tested processes capable of producing particular forms. Their combination widened the possibilities for evaluating interpretations of landscape development. It also made uncertainty more specific. A disagreement might concern the identification of a deposit, the meaning of a dated surface or the applicability of a mechanism under particular conditions. Such distinctions gave later investigations clearer questions to resolve and reduced reliance on explanations supported chiefly by resemblance between landforms.

Historical climatology developed an especially recognisable research tradition around Rudolf Brázdil and his collaborators in Brno. Its achievement was to make documentary evidence

useful for systematic investigation of weather, climate and their consequences. Brázdil's 2005 review with Christian Pfister, Heinz Wanner, Hans von Storch and Jürg Luterbacher, Historical climatology in Europe—the state of the art, placed this work within a European methodological synthesis. It assessed the properties of documentary sources, reconstruction methods and research on climatic anomalies and disasters. The paper connected the recovery of historical observations with questions that could be examined by climate science, while retaining attention to the circumstances in which human witnesses had recorded the weather.

Petr Dobrovolný's work provided an important quantitative extension of this tradition. A collaborative paper published in 2010 reconstructed monthly, seasonal and annual temperatures for Central Europe back to 1500 using documentary indices and instrumental records. Its procedures included the correction of instrumental inhomogeneities and evaluation of the relationship between overlapping forms of evidence. The study transformed dispersed historical information into a reconstruction whose performance and uncertainty could be assessed. Dobrovolný and Brázdil's participation also illustrates how a Czech research concentration operated through international cooperation, with evidence and expertise drawn from several European countries. The resulting chronology belonged to a shared regional problem whose spatial scale exceeded the national territory.

Tree-ring research subsequently enlarged the temporal and analytical reach of hydroclimatic reconstruction. Ulf Büntgen and colleagues' 2021 *Nature Geoscience* paper, Recent European drought extremes beyond Common Era background variability, included contributions from Otmar Urban, Petr Dobrovolný and Miroslav Trnka. Stable carbon and oxygen isotopes in oak rings were used to reconstruct central European summer hydroclimate across more than two millennia. The analysis placed recent drought conditions within this long reconstruction. Its disciplinary significance lay in combining precisely dated biological material, laboratory analysis and climatic interpretation. The geographical reach and seasonal meaning of the reconstructed signal remained essential to understanding what the result could establish.

The continued vitality of documentary approaches was also evident in Brázdil and colleagues' 2024 analysis of Czech flash floods during 2001–2023. The team included Dominika Faturová, Monika Šulc Michalková, Jan Řehoř, Martin Caletka and Pavel Zahradníček. Documentary evidence supplied information about events that standard hydrological observations could miss. The publication connected the geographical distribution of floods with their triggers and human impacts. Its significance for the history of the research school was the adaptation of an established approach to a contemporary observational problem. Historical source criticism and modern environmental monitoring could contribute to the same investigation, even when the events themselves belonged to the recent past.

Hydrological research within physical geography similarly benefited from closer connections between measurement, modelling and the spatial organisation of catchments. Jakub Langhammer's 2019 paper UAV Monitoring of Stream Restorations examined repeated aerial surveys of an urban stream in Prague. The work tested what such observations could establish about the relationship between a restoration plan, the channel that actually developed and subsequent environmental changes. Comparable surveys allowed the intervention to be evaluated over time. Digital surveying became a means of asking a physical-geographical

question about channel behaviour and riparian conditions, with the limitations of the technique forming part of the assessment.

Michal Jeníček and Ondřej Ledvinka's 2020 study of snowmelt and seasonal runoff supplied another example of explanatory progress. Their modelling of 59 Czech mountain catchments during 1980–2014 was evaluated against observed runoff and snow water equivalent. The results connected winter snow conditions with groundwater recharge and summer low flows. For physical geography, the importance of this work lay in relating different seasons and components of the catchment water balance. Jeníček's university-based research and Ledvinka's contribution from the Czech Hydrometeorological Institute also demonstrate the value of cooperation between academic analysis and the organisations responsible for systematic environmental observations.

In landscape research, Zdeněk Lipský's work helped establish how historical transformation could be investigated through the spatial arrangement of landscape elements. His 1995 paper The changing face of the Czech rural landscape examined an agricultural landscape in Central Bohemia and distinguished the information supplied by land-use statistics from the finer structure of patches, lines and connecting elements. The contribution gave an early post-1993 expression to a persistent concern of Czech landscape geography: changes in area totals required interpretation alongside changes in spatial composition. Its significance was therefore both historical and methodological, directing attention towards features through which human activity altered ecological relationships within the landscape.

Antonín Buček and Jan Lacina sustained a complementary approach through geobiocoenology. Their *Geobiocenologie II*, published in a 2007 edition, organised knowledge of Czech landscapes through relationships between communities and their environmental settings. The work gave students and researchers a systematic language for considering the ecological significance of altitude, nutrient conditions and moisture. Through this educational and interpretative function, it helped sustain a research tradition whose concepts guided observation and comparison. The framework also provided a basis for considering new field evidence and changes in environmental conditions.

Martin Culek's contribution to biogeographical synthesis is particularly clear in the 2013 monograph *Biogeografické regiony České republiky*, written with Vít Grulich, Zdeněk Laštůvka and Jan Divíšek. Its accounts connected regional geology, relief, soils and climate with biological characteristics and vegetation. As a collective work, it brought geographical, botanical and zoological expertise into a common spatial framework. The book's achievement was the articulation of regional individuality through the relationships among these components. It also offered a setting within which more specialised findings could be interpreted, preserving the value of synthesis alongside the increasing detail of ecological datasets and statistical analyses.

The adjoining field of vegetation science made contributions of considerable importance to biogeography and geoecology. Milan Chytrý's 2012 review Vegetation of the Czech Republic: Diversity, ecology, history and dynamics assembled a national account relating communities to environmental conditions and post-glacial history. His work illustrates an area in which the

intellectual resources of physical geography overlapped with those of botany. Its relevance to geographical analysis lay in the treatment of vegetation as spatially differentiated and historically formed. The review also made an extensive body of Czech knowledge accessible in English, supporting comparison with other parts of Europe and providing a substantial reference for students approaching the country's natural systems.

Lubomír Tichý's JUICE software, described in the *Journal of Vegetation Science* in 2002, represents a different kind of influential publication. It presented tools for editing, classifying and analysing vegetation tables and databases, with facilities for examining species associations and preparing comparative summaries. Other investigators could use these procedures to reorganise accumulated field records and examine them through explicit analytical operations. Within the wider history of Czech environmental research, this was an achievement in building shared scientific capacity: an investigator's contribution could take the form of a working instrument used in studies beyond the original project.

The *Landscape Atlas of the Czech Republic*, published in 2009 under the coordinating editorship of Tatiana Hrnčiarová, Peter Mackovčin and Ivan Zvara, brought several of these traditions into a large cartographic synthesis. Analytical maps and synthetic representations connected natural conditions with historical development, contemporary landscapes and cultural dimensions. The atlas's importance for physical geography lay in the relationships that could be considered across this common cartographic setting. It gave specialised results a place within an account of the country as a whole. Such a work required substantial coordination, and its authorship and editorial labour remind us that the production of a landmark publication could itself constitute a major collective scientific achievement.

Polar research demonstrates the importance of another form of scholarly contribution: establishing the practical conditions in which a sustained programme could operate. Pavel Prošek and colleagues' 2013 paper on the facilities of the Johann Gregor Mendel Antarctic station examined technical and technological solutions, with particular attention to energy sources. This publication documented work underlying the production of environmental observations in a remote setting. Prošek's contribution to Czech physical geography must therefore be considered alongside the responsibilities involved in making repeated field research feasible. The scientific output of a polar programme depended on such arrangements as well as on the investigations subsequently undertaken from the station.

The consolidation of that programme became visible in publications by researchers maintaining and extending its observations. A 2025 paper by Filip Hrbáček, Michaela Kňažková, Kamil Láska and Lucia Kaplan Pastíriková assessed active-layer warming and thickening near the Mendel station using a decade of measurements. Its importance here lies in the continuity of the research community and its record. Several researchers contributed to an analysis made possible by successive field seasons and a persistent monitoring framework. This offers a concrete example of how a scientific school could develop through responsibility for shared observations, with later investigators able to ask questions that the initial seasons alone could not answer.

Educational publications supplied another means through which research experience entered the wider discipline. Karel Kirchner and Irena Smolová's *Základy antropogenní geomorfologie*, published by Palacký University in Olomouc in 2010, gave university teaching a focused treatment of human influence on landforms. Its subject connected geomorphology with the investigation of transformed landscapes, an important concern throughout the period. The book also illustrates the contribution of centres whose influence cannot be assessed solely through international research articles. Teaching materials provide terminology, organise bodies of knowledge and help students recognise phenomena in the field. Their role becomes especially apparent when considering how specialised research is reproduced across successive cohorts.

The publications considered here performed several different scientific functions. A regional lexicon supported consistent geographical identification; a review assessed the state of a method; an experimental paper tested an explanation; and software made analytical procedures available to others. Their influence should consequently be evaluated through what they enabled subsequent researchers to do. National-language monographs and teaching texts maintained access to detailed regional knowledge, while English-language articles and edited volumes placed that knowledge within international discussion. These forms of publication supported one another, giving physical geography both a regional foundation and means of communicating beyond it.

Individual distinction also needs to be understood in relation to collective work. An editor could assemble a synthesis that no single author could have produced. A specialist in archives, tree rings, numerical modelling or field instrumentation could supply an essential part of an explanation led by another researcher. The studies reviewed above repeatedly crossed institutional and disciplinary boundaries. Their authorship therefore records relationships as well as individual accomplishments. The evidence supports a history in which established scholars formulated durable questions and later teams revised the means of investigating them, while cooperation continued to create new combinations of expertise.

By 2025, Czech physical geography possessed both substantial reference works and research programmes capable of generating new explanations from increasingly detailed evidence. Its schools had maintained knowledge of particular regions while extending the temporal and geographical range of investigation. The most enduring achievements were those whose assumptions could be examined and whose observations or methods remained available for further work. Through the contributions of the scholars discussed here, the discipline strengthened its ability to connect landforms, water, climate and living systems within explanations of environmental development and change.

Part Four

Geological Sciences and the Study of the Earth’s Crust

Geological Research after 1993: Institutional Continuity, Changing Priorities and International Connections

Geological research in the Czech Republic after 1993 developed through the renewal and adaptation of a substantial inherited scientific tradition. The new state possessed experienced research institutions, extensive geological documentation and university schools whose questions reached well beyond its borders. Over the following three decades, their work acquired a broader range of environmental responsibilities and stronger connections with international programmes. Investigations of the Earth’s crust continued alongside research on groundwater, mineral resources and the consequences of using the subsurface. The period is therefore best understood through the relationship between accumulated regional knowledge and changing expectations of what geological science should explain and provide.

The physical setting encouraged this combination of continuity and outward engagement. Much of the country belongs to the Bohemian Massif, whose geological structures extend into Germany, Poland and Austria. Its eastern margin approaches the Western Carpathian system. Understanding this territory requires the reconstruction of events that preceded the modern state by hundreds of millions of years and involved regions now divided between several countries. A national geological service could organise observations within administrative boundaries, while the scientific interpretation of those observations demanded a wider view. International cooperation consequently addressed the scale of the geological problems themselves, as well as the practical needs of research.

The Czech Geological Institute, renamed the Czech Geological Survey in 2002, remained a principal link between systematic investigation and public responsibility. Its institutional history extended back to 1919. At the beginning of the period considered here, its accumulated maps, collections and field records already constituted an important scientific resource. The change of state framework in 1993 gave these activities a new national setting, while preserving the need to maintain and revise knowledge of the territory. The Survey’s subsequent development joined geological research with the provision of information for environmental management, planning and the assessment of resources and hazards.

The early reorientation can be seen particularly clearly in the Institute’s annual report for 1995. It recorded the completion of geological mapping at a scale of 1:50,000 and described the transition towards geographical information systems in preparing geological and thematic maps. Environmental projects accounted for 54% of the institution’s total budget that year. These developments were closely related. Regional mapping supplied evidence needed to investigate contaminated environments, groundwater conditions and the effects of earlier industrial activity. Geological expertise was being applied to questions whose public

importance had increased during the post-socialist transformation, while the systematic description of rocks and structures continued to provide its foundation.

This relationship gave the mapping programmes a significance beyond the production of finished sheets. A geological map records an interpretation assembled from observations of unequal density and certainty. The introduction of digital systems made such information easier to combine with borehole records and other environmental data, but the quality of the interpretation still depended on field judgement. In this respect, methodological renewal increased the value of institutional memory. Earlier observations could be reconsidered in the light of new questions, provided that their location, meaning and limitations remained intelligible. The preservation of documentation was therefore part of the research process itself.

The Academy's Institute of Geology entered the new state period after an important reorganisation of its own. Re-established in 1990 following earlier mergers, it maintained research traditions in petrology, geochemistry, palaeontology, stratigraphy and Quaternary studies. Its history records cooperation through international programmes, including IGCP and PAGES, alongside grant-supported projects. These arrangements provided several routes through which specialised investigations could continue. A researcher studying a fossil group, a sedimentary sequence or the chemical history of a rock could work within an established disciplinary community while contributing to a project organised around a broader environmental or geological question.

University developments show how this continuity was accompanied by changes in intellectual organisation. At Charles University, the Institute of Petrology and Structural Geology assumed its modern form in the early 1990s under Karel Schulmann. The closer connection between petrology and structural geology encouraged the interpretation of mineral and rock histories alongside evidence of deformation. At the Institute of Geology and Palaeontology, the appointment of Ivo Chlupáč in the early 1990s strengthened an established concentration of research on the Barrandian. Both examples joined long familiarity with particular rocks and sequences to questions of wider scientific relevance. Renewal could proceed through a different relationship between existing specialisms, supported by scholars able to connect regional evidence with international debates.

In Ostrava, institutional change reflected the altered circumstances of a major mining region. The Institute of Geological Engineering was established in 1994 through the merger of departments concerned with geology and mineralogy, applied geology and economic geology. Its later designation became the Department of Geological Engineering in 2018. The department's history also records the introduction of geoscience and industrial tourism teaching in 1997 in response to mining contraction and opportunities to reuse former workings. This educational development offers a concrete illustration of the changing responsibilities surrounding geological knowledge. Expertise developed in relation to extraction could contribute to the interpretation, management and subsequent use of places shaped by mining.

The research community was also connected through less formal relationships between institutions. Masaryk University's Department of Geological Sciences developed cooperation

with the Geological Survey, museums, public bodies and companies through projects, teaching and professional training. Such relationships gave university research access to practical questions and field experience, while providing external organisations with analytical expertise and trained graduates. Their importance is visible in the range of activities involved, from joint investigations to excursions and internships. This distributed structure helped maintain connections between the acquisition of geological knowledge and the many settings in which it was used.

Changes in scientific publishing offer unusually precise evidence of international reorientation. In 1993, the former *Časopis pro mineralogii a geologii* became the *Journal of the Czech Geological Society*, with English-language publication and more demanding review procedures directed towards an international readership. Online tables of contents followed in 2001 and PDF articles in 2003. The *Journal of Geosciences* succeeded it in 2007. An agreement between the Geological Society and the Geological Survey also concentrated palaeontology, sedimentology and stratigraphy in the partner *Bulletin of Geosciences*, while the *Journal of Geosciences* focused on crystalline geology and associated fields. These decisions altered the organisation and circulation of Czech research as well as its presentation.

The wider international setting had a history extending well before 1989. Survey geologists had participated in overseas mapping, mineral exploration and scientific organisations under earlier political conditions. Their post-1993 connections developed from this uneven but substantial experience. The Survey's historical account records the renewal of work in Nicaragua in 1997 through Czech development assistance and the resumption of UNESCO-linked GEOCHIM training courses in 1999. Its membership of the Forum of European Geological Surveys had begun in 1992, followed by participation in the combined EuroGeoSurveys framework after 2004. These examples show several forms of engagement operating together: bilateral field projects, professional education and coordination among national surveys.

Deep investigations of the Bohemian Massif demonstrate what international cooperation could make scientifically possible. The CELEBRATION 2000 seismic experiment produced evidence for interpreting crustal structures across Central Europe. A 2005 study led by Pavla Hrubcová, with Czech, Polish and other international collaborators, used seismic tomography and wave modelling, supplemented by gravity modelling, to investigate the massif's crust and uppermost mantle. Differences between major tectonic domains became visible at depth, including contrasting forms of the transition between crust and mantle. The study connected geological units recognised at the surface with evidence acquired through a coordinated experiment whose scale required the resources and expertise of several countries.

This work also illustrates a changing relationship between geology and geophysics. Geological interpretation could draw upon increasingly detailed images of structures inaccessible to direct observation, while seismic models required constraints from rock properties and regional geological history. Neither form of evidence could supply every part of the explanation. Their combination made it possible to ask more specific questions about crustal assembly and the preservation of older structures. Within the history of geological research, such

cooperation expanded the range of observations through which a regional interpretation could be examined and challenged.

European integration during the 2000s provided a broader organisational setting for these developments. Scientific ties already crossed national borders, but shared programmes increasingly required agreement about how observations were described and exchanged. The OneGeology-Europe project, launched in 2008, aimed to make geological mapping available through a common European framework. The Czech Geological Survey was responsible for a multilingual metadata catalogue. This contribution involved the information needed to understand and locate geological datasets, rather than simply assembling a picture of adjoining territories. Differences in terminology, classification and mapping practice had to be made visible if data from separate national traditions were to be used together.

Institutional changes within the same decade also affected the conditions of research. The Institute of Geology entered the register of public research institutions on 1 January 2007. Its registered responsibilities joined theoretical and applied geology with environmental science, scientific publication and doctoral training in cooperation with universities. International projects and exchanges formed part of this remit. The significance of the change for the present account lies in the formal combination of research, education and wider scientific services within a continuing organisation. Institutional history and intellectual development followed different timescales, even when new organisational arrangements helped determine how a research programme could be sustained.

A further consolidation concerned geological documentation. From 1 January 2012, the activities, workplaces and staff of the formerly separate Czech Geological Survey–Geofond became part of the Survey. The merger brought responsibility for an extensive documentary inheritance into a unified institution. Reports and material records could retain scientific value long after the exploration programme that had produced them had ended. Later researchers might ask about groundwater movement, mineral associations or the suitability of a rock environment for a use scarcely considered when a borehole was first drilled. Access to this evidence reduced the need to begin every investigation with new fieldwork and made the quality of archived descriptions a continuing scientific concern.

Research on the Variscan evolution of Europe continued to give Czech geology a substantial role in international theoretical discussion. The 2014 volume *The Variscan Orogeny: Extent, Timescale and the Formation of the European Crust*, edited by Karel Schulmann, José Ramón Martínez Catalán, Jean-Marc Lardeaux, Vojtěch Janoušek and Giacomo Oggiano, brought the Bohemian Massif into a synthesis extending from Iberia across the European Variscan belt. Its contents connected structural relationships with magmatism, metamorphism and the timing of crustal events. Czech contributions thus participated in the interpretation of a continental system. Detailed regional studies supplied evidence for explanations whose relevance depended on comparison with other parts of Europe.

The analytical means available to these investigations also widened. At Charles University, petrological and structural research combined microscopy and mineral analysis with experimental work on magmatic processes and the interpretation of deformation. These

approaches allowed investigators to connect the small-scale record preserved in minerals with questions about the movement and transformation of crustal material. The scientific task involved reconstructing the conditions represented by a mineral assemblage and relating them to the sequence of events recorded in the surrounding rocks. Greater analytical detail made the links between a sample, its field setting and the proposed geological history more consequential.

A comparable widening of perspective is expressed in the Institute of Geology's Earth-system conception of research. Its programme connects the geological and biological past with the interpretation of the present environment. Interactions between organisms and geological processes are considered in relation to atmospheric composition, weathering, sedimentary basins and the formation of resources. This conception gives palaeontology and sedimentary research a place within explanations of environmental development. It also provides a framework in which older specialisms can address common questions without losing the careful description and classification on which their evidence depends.

The benefits of combining established material with new analytical opportunities are apparent in palaeontology. A 2023 *Nature* paper by Petr Kraft, Valéria Vaškaninová, Michal Mergl, Petr Budil, Oldřich Fatka and Per Ahlberg investigated exceptionally preserved trilobite gut contents using synchrotron imaging. The collaboration involved Charles University, the University of West Bohemia, the Geological Survey and Uppsala University. Here a specimen from a classic Czech fossil-bearing region supported questions about the biology of an extinct animal through an international combination of expertise and instrumentation. The example shows how the scientific possibilities of a regional fossil record could change as methods and partnerships developed.

By the later 2010s, European cooperation increasingly concerned enduring access to research outputs. The Geological Survey became one of the founding participants in the European Geological Data Infrastructure in 2016. The GeoERA programme subsequently connected projects on raw materials, geoenergy and groundwater with a dedicated information-management project. Its thematic projects operated during 2018–2021, and their results were made available through this shared infrastructure. The historical change concerned what happened after an individual project ended. Maps and datasets could remain accessible within an organised system, accompanied by information needed to assess their scale, methods and suitability for further investigation.

The CzechGeo/EPOS infrastructure provided a related development in observations of the solid Earth. It coordinated permanent observatory measurements and temporary field monitoring across participating Czech institutions and connected them with the European Plate Observing System. Seismological, geodetic and other geophysical observations supplied complementary evidence of the Earth's structure and behaviour. For geological research, the value lay in the possibility of relating regional interpretations to sustained measurements. Maintaining instruments and their records became part of a shared scientific undertaking, with benefits that accumulated over a longer period than the field campaign or research grant through which a particular question was first investigated.

New public priorities brought further uses of subsurface knowledge into prominence. By 2024, the Geological Survey's research on critical raw materials included rare earth elements and other metals investigated through international projects such as SuMREE and DeepBEAT. The latter concerned mineralisation in the Čistá–Jesenice Massif. These projects linked questions about the distribution and origin of mineral resources with renewed attention to European supply. The research depended on familiar geological disciplines, including mineralogy, geochemistry and structural interpretation. Changes in economic and policy priorities gave additional reasons to revisit the evidence held in established mineral districts.

Geoenergy research similarly expanded the questions asked of the geological environment. Work on geothermal resources and underground storage connected structural geology and hydrogeology with geophysics, geochemistry and reservoir engineering. The Czech–Norwegian CO2-SPICER project, completed in 2024, prepared geological knowledge and models for a proposed pilot storage facility in a depleted carbonate gas reservoir in south-eastern Moravia. Its work included static and dynamic 3D modelling. This was an investigation of the conditions required for a possible future use of the subsurface. The distinction between assessing suitability and demonstrating successful operation remained essential to interpreting its results.

Research associated with radioactive waste disposal created another sustained demand for detailed understanding of the crust. In 2024, cooperation between the Geological Survey and the Radioactive Waste Repository Authority included geological and hydrogeological mapping of candidate areas, together with characterisation of the rock environment at the Bukov Underground Research Facility. Such work required the connection of observations made at different scales and through different methods. A description of rock type alone could provide only part of the evidence needed. Fractures, groundwater conditions and the behaviour of the rock environment under investigation became central to the questions being asked.

The Geological Service for Europe project, which began in September 2022 and was still in progress at the end of 2025, placed these interests within a wider European programme. With the Czech Geological Survey among its partners, it sought to harmonise geological information and develop shared services supporting the energy and climate transitions. Its objectives reflected the difficulty of using extensive national data holdings together when their descriptions and organisation differed. For Czech geology, participation involved contributing a mature regional knowledge base while helping develop the means by which that knowledge could be compared and used at European scale.

The outward reach of Czech expertise also remained visible in research undertaken beyond continental Europe. In 2025, Hrubcová, Václav Vavryčuk, Tomáš Fischer and Jana Doubravová published an analysis of earthquakes preceding Iceland's 2021 Fagradalsfjall eruption. Their work examined stress changes and the role of magmatic fluids in fault behaviour. The example extends the earlier picture of international cooperation: Czech researchers contributed specialised analytical methods to an active geological setting outside their own country. Regional research traditions could support this wider engagement by developing expertise applicable to related physical processes under different geological conditions.

Across the period, institutional continuity proved valuable because geological knowledge remained dependent on accumulated observations, collections and experience. Changing priorities created opportunities to reinterpret that inheritance, from the environmental concerns of the 1990s to later work on energy, storage and critical resources. International connections enlarged the scale of experiments and comparisons, while digital infrastructures changed how evidence could circulate and remain available. By 2025, Czech geological research combined these developments with continuing investigation of the deep history and structure of the Earth's crust. Its capacity for renewal rested on keeping specialised evidence connected to the broader questions for which it could provide an answer.

Structural Geology and Tectonics: The Bohemian Massif, the Western Carpathians and European Geological Evolution

Structural geology and tectonics acquired a particularly strong international dimension in Czech research between 1993 and 2025. The Bohemian Massif offered an extensive record of the assembly and deformation of the European crust, while the Western Carpathians preserved the effects of a younger orogenic system along its eastern margin. Investigators increasingly connected structures observed in the field with mineral ages, thermal histories and geophysical evidence from depth. These developments produced more detailed reconstructions of geological events and sharpened disagreements about their interpretation. Czech contributions became influential through their ability to connect carefully documented regional relationships with questions about how continental crust is assembled, buried and returned towards the surface.

Two chronologies must be kept in view when considering this development. The history of the research belongs to the decades after 1993; the events reconstructed by that research extend across much of the geological past. The Variscan orogeny, especially its Devonian and Carboniferous stages, shaped much of the basement exposed in the Bohemian Massif. Later deformation associated with the Alpine system affected that older crust and produced the principal architecture of the Western Carpathians. Present geographical proximity therefore brings together records of several geological cycles. The task of structural interpretation is to establish which relationships belong to each cycle and how later events modified the evidence of earlier ones.

A useful starting point for the first post-1993 decade is the 1995 synthesis *Pre-Permian Geology of Central and Eastern Europe*, edited by R. D. Dallmeyer, Wolfgang Franke and Klaus Weber. It developed from an international meeting held in 1990, when political change had opened new possibilities for scientific exchange. The volume organised geological knowledge across regions whose research traditions had long been divided by national and political boundaries. Its treatment of the Sudetes, the Moldanubian region and the Moravo-Silesian zone placed Czech evidence within a larger framework. For the history of the discipline, the book marks the consolidation of a shared regional discussion at the beginning of the period examined here.

The geological vocabulary inherited by that discussion remained useful, but its tectonic meaning required continuing examination. Names such as Saxothuringian, Teplá–Barrandian and Moldanubian identify major parts of the massif with different rock associations and histories of deformation. Their boundaries could be mapped through faults, thrusts and zones of sheared rock. Reconstructing what those boundaries had once represented was more difficult. A present contact might preserve evidence of an ancient collision, subsequent displacement along the mountain belt, or several episodes of movement. Structural geology consequently developed through the effort to relate the visible arrangement of units to a sequence of processes.

Geochronology helped turn that sequence into a more closely constrained history. A 2002 study by Dirk Marheine, Václav Kachlík, Henri Maluski, František Patočka and Andrzej Żelaźniewicz used argon-isotope ages from the West Sudetes to investigate successive tectonic and thermal events. The work related mineral ages to evidence of metamorphism, exhumation and later shearing across a mosaic of units. It demonstrated how regions that now adjoin one another could preserve different paths through the same broad orogenic cycle. The contribution of Czech specialists formed part of a collaboration extending into neighbouring research communities, appropriate to a geological area shared across the Czech–Polish border.

The interpretation of such ages also demanded a more explicit connection between laboratory measurements and field relationships. The time recorded by a mineral could concern its growth, cooling or subsequent disturbance. A granite’s crystallisation age constrained the timing of deformation differently according to whether its fabric formed while magma was still present or after solidification. These distinctions became central to increasingly detailed tectonic reconstructions. The growth in analytical precision made the identification of the event being dated especially important. A numerical age acquired geological meaning through its relationship to the surrounding structures and the processes that could have produced them.

Research on the Sudetes illustrates why international comparison remained indispensable. Stanisław Mazur, Paweł Aleksandrowski, Ryszard Kryza and Teresa Oberc-Dziedzic’s 2006 review of the Polish Variscides considered the structural mosaic of the Sudetes together with its Czech continuation. Contrasting histories of deformation and cooling complicated the extension of classical Variscan zones across the region. Later strike-slip displacement had further altered the arrangement of units. This Polish synthesis supplied an important comparative setting for Czech investigations. It also demonstrated a recurrent problem in European tectonics: the correlation of structures separated by faults required evidence of their earlier relationships, beyond similarity in their present appearance.

During the 2000s, Czech structural and petrological research made increasingly ambitious contributions to the mechanics of mountain belts. A 2008 study led by Karel Schulmann, with Ondřej Lexa, Pavla Štípská and other collaborators, developed a model of vertical extrusion followed by horizontal flow of deep crustal material in the eastern Variscan belt. The interpretation combined structural, petrological and chronological evidence with gravity information. It proposed that rocks from the hot, deep root of the orogen had first moved

upwards and subsequently flowed laterally at shallower crustal levels. The Bohemian Massif thereby became a setting in which the behaviour of deeply buried continental crust could be investigated through a preserved geological record.

The model gave structural observations a direct role in reconstructing movement through the orogenic crust. Steep and flatter fabrics were interpreted in relation to successive stages of deformation, while pressure and temperature evidence helped establish the depths represented by the rocks. These elements had to form a coherent history: a proposed movement needed to account for the sequence of structures and the conditions recorded during their development. The wider significance lay in relating the geometry of deformation to the physical behaviour of hot crust. This work connected regional geology with questions also encountered in large mountain belts elsewhere in the world.

Schulmann and colleagues' 2009 synthesis, An Andean type Palaeozoic convergence in the Bohemian Massif, extended the discussion to the organisation of convergence across the region. It related Saxothuringian subduction, the development of a thickened crustal root and the later influence of the Brunia continental block. In this interpretation, indentation helped drive the redistribution of deep crustal material. The proposed history connected the internal architecture of the massif with the deformation and sedimentary record of its eastern foreland. Its publication in *Comptes Rendus Geoscience* also reflected the close Czech–French connections through which this research developed and entered international discussion.

A complementary approach examined the relationships around granitoid bodies. In 2014, Jiří Žák, Kryštof Verner, Vojtěch Janoušek and their co-authors presented a plate-kinematic model of the massif's assembly constrained by structures associated with plutons. Their reconstruction related successive episodes of subduction, shortening, exhumation and strike-slip movement to the distribution and timing of magmatism. Intrusions supplied reference points within the deforming crust because their contacts and internal fabrics could preserve relationships with surrounding structures. The study showed how detailed investigations of individual bodies could contribute to a regional account of movement. It also made the temporal organisation of the proposed tectonic stages open to examination through further dating and mapping.

These models addressed partly overlapping questions at different scales. The history of plate convergence concerned the movement of large crustal blocks, while models of extrusion and channel flow examined how material behaved within a thickened orogen. Evidence from plutons helped connect both levels of interpretation with particular places and times. This diversity was productive when assumptions and constraints were made explicit. A model could be assessed through the structures it explained, the events it required and the observations that remained difficult to accommodate. The development after 1993 thus included a more demanding discussion of how regional tectonic histories should be constructed.

Deep seismic research supplied another set of constraints. Pavla Hrubcová, Piotr Środa and the CELEBRATION 2000 Working Group's 2008 study used the CELEBRATION 2000 and ALP 2002 experiments to investigate the eastern termination of the Variscan belt. It identified contrasting crustal properties along profiles extending through the Eastern Alps, the Moravo-

Silesian zone and regions farther north-east. Differences in the transition between crust and mantle could be considered alongside tectonic boundaries mapped at the surface. Such observations allowed geological interpretations to be tested against the architecture of the deeper crust, while retaining uncertainty about how particular seismic contrasts related to rock types and inherited structures.

The contact between the Bohemian Massif and the Western Carpathians received more direct attention in a 2010 analysis of SUDETES 2003 data led by Hrubcová. Its principal profile crossed the massif and the Carpathians before reaching the Pannonian Basin. Seismic and gravity modelling revealed marked lateral changes in crustal structure and the shallower sedimentary cover. The work gave researchers a continuous section across regions formed and reworked during different orogenic cycles. It also connected Czech investigations with Polish, German, Slovak and Hungarian expertise. The boundary between geological provinces could now be examined through observations from depth as well as through their contrasting surface geology.

The older massif's subsequent history also required attention. A 2012 study by Martin Danišík, Petra Štěpančíková and Noreen Evans combined several thermochronological methods to examine denudation and faulting around the Sudetic Marginal Fault. It inferred substantial Late Cretaceous burial followed by cooling and exhumation, challenging reconstructions that had treated parts of the region as persistently exposed land. The study related the later evolution of the fault to changes in the surrounding blocks. Its contribution was to extend structural interpretation beyond Variscan assembly and to investigate how younger events had helped produce the geological exposures and relief available to present-day observers.

The Western Carpathians presented a related problem through a different record. Within Czech territory, the Outer Western Carpathians and their foreland preserve sedimentary successions incorporated into a fold-and-thrust belt and deposited in adjoining basins. Much of the evidence for the older internal parts of the Carpathian orogen lies farther east, particularly in Slovakia. Czech investigations therefore depended on a regional perspective broad enough to connect local nappes with the development of the whole system. The relevant distinction was between the origin of the rocks and the later movements that brought them into their present position. A sediment deposited in a marine basin could subsequently travel within a thrust sheet and undergo further faulting.

Frank J. Picha, Zdeněk Stráník and Oldřich Krejčí's 2006 account of the Outer Western Carpathians and their Czech foreland assembled a substantial body of regional knowledge within an international synthesis. The chapter connected depositional history with the structure of the thrust belt, its underlying foreland and hydrocarbon systems. Its research setting gave boreholes and seismic observations an important place alongside surface geology. Although prepared partly for an applied readership, the synthesis addressed fundamental relationships between sedimentary basins and deformation. For Czech tectonics, it provided an extensive account of the western end of the Carpathian system and its connection with the Eastern Alps.

In this setting, the geometry of a nappe carried information about more than the direction of transport. Nappes are large bodies of rock displaced along thrust surfaces; their internal successions can preserve the histories of the basins from which they originated. Repetition of strata, overturned beds and the juxtaposition of formations of different ages help establish their structure. Fossil evidence can distinguish units whose rocks look deceptively similar. The investigation of Carpathian tectonics therefore maintained a close relationship with stratigraphy and sedimentology. This connection gave regional field knowledge continuing importance as deeper observations and more elaborate models became available.

Czech regional interpretations also benefited from efforts to correlate the wider Alpine–Carpathian–Dinaridic system. Stefan Schmid and colleagues' 2008 synthesis combined a tectonic map with crustal-scale sections to examine how its units related across national and geographical divisions. The reconstruction treated the present architecture as the product of repeated deformation, including movements that had disrupted earlier connections. This wider work supplied a framework within which the Western Carpathians could be compared with adjoining parts of the Alpine system. Its value for Czech research lay in making explicit the regional relationships that a local cross-section alone could leave unresolved.

A companion development concerned the restoration of movements in map view. Kamil Ustaszewski and colleagues' 2008 reconstruction estimated the translation and rotation of tectonic units since the Early Miocene. It provided a semi-quantitative account of the earlier configuration of the Alps, Carpathians and Dinarides, including the lateral displacement of the Alpine–Carpathian–Pannonian block. For interpreting Czech and Slovak structures, such work mattered because directions measured today could have been changed by later rotation. Reconstructing an earlier movement required consideration of the subsequent history of the unit in which the observation was made. Regional tectonics consequently became a problem of restoring changing geometries through time.

Dušan Plašienka's 2018 synthesis of early Alpine evolution offered a detailed Slovak perspective on the Western Carpathian record. It related Triassic rifting, Jurassic subduction and Cretaceous to Eocene development of the orogenic wedge. The account considered how relatively continuous large-scale processes could produce episodes of more intense deformation in the rock record. This distinction helped explain why local tectonic phases need not correspond directly to abrupt changes in plate motion. Its relevance to Czech research arises from the geological continuity of the Carpathian system and the need to compare evidence preserved in different parts of it.

The question of how many oceans and continental fragments preceded the European Variscan collision remained open to renewed debate. Wolfgang Franke, Robin Cocks and Trond Torsvik's 2017 review proposed a reconstruction combining geological, palaeontological and palaeomagnetic constraints on several intervening seaways. Their interpretation placed Bohemia within a broader history of fragments derived from the northern Gondwana margin. The importance for Czech tectonics was the requirement that regional models remain consistent with evidence beyond the massif. Fossil distributions, oceanic remnants and the timing of convergence elsewhere in Europe supplied constraints that could not be obtained from a local structural study alone.

Franke and Żelaźniewicz returned to the Bohemian Massif in a critical review published in 2023. They questioned aspects of several recent reconstructions, including correlations between deeply metamorphosed units and their proposed source regions. Their account emphasised the need to assess laboratory results alongside stratigraphic and regional structural relationships. These criticisms should be understood as part of an active scientific disagreement. The authors advanced their own reconstruction, and the review's conclusions do not constitute a single settled interpretation of the massif. In a history extending to 2025, the debate demonstrates the continued scientific importance of the Czech geological record and the difficulty of recovering a unique sequence of events from its repeated deformation.

New work on the Western Carpathian basement further connected Variscan and Alpine research. A 2024 study led by Igor Soejono, with Stephen Collett, Milan Kohút, Janoušek, Schulmann and other collaborators, used zircon ages, hafnium isotopes and whole-rock geochemistry to investigate older source regions and depositional settings. The results supported a proposed reconstruction linking the basement's early development with parts of northern Gondwana. Its evidence concerned material later involved in both Variscan and Alpine collisions. The study thus examined relationships obscured by younger deformation and showed how Czech–Slovak cooperation could address the prehistory of crust now preserved within the Carpathian belt.

Digital representation became more closely integrated with structural explanation towards the end of the period. Jaroslava Pertoldová and colleagues' 2024 study of the Klenov Pluton combined geological mapping, uranium–lead dating and 3D visualisation with geophysical evidence. Its reconstruction investigated the form and emplacement of a late-orogenic granite body within the Pelhřimov Core Complex. Here a model made the proposed subsurface geometry easier to relate to the mapped contacts and analytical results. The scientific advance depended on the combination of evidence supporting that geometry. 3D representation provided a means of examining the interpretation and identifying where additional observations might distinguish between alternatives.

At the same time, new exposures continued to revise the local evidence. Miroslav Bubík's 2025 study of a road cutting near Starý Jičín documented a complex tectonic slice involving formations of the Silesian and Subsilesian units. Field observations were combined with petrography and micropalaeontology, and the structure was interpreted as a duplex, in which thrust-bounded slices are stacked between bounding faults. The work refined an area previously investigated for geological mapping. Its place at the close of this account is instructive: even in a well-studied region, a newly accessible section could alter the understanding of relationships obscured by younger cover.

Across these developments, Czech structural geology gained strength through its capacity to connect different kinds of evidence. Detailed mapping retained the spatial relationships on which interpretation depended. Dating distinguished successive events, while petrological and geophysical investigations supplied information about conditions and structures beyond direct observation. International comparison tested whether a regional reconstruction could also account for neighbouring parts of an orogenic belt. The resulting models remained open

to revision because each depended on decisions about which observations belonged to the same process and which recorded later modification.

By 2025, the Bohemian Massif and the Western Carpathians had become complementary settings for investigating European crustal evolution. The massif contributed evidence of continental assembly and the behaviour of deep orogenic crust; the Carpathian region showed how older material was incorporated into younger systems of basins, thrust sheets and displaced blocks. Czech researchers participated in this development through regional expertise, methodological contributions and sustained cooperation with colleagues abroad. The history after 1993 is therefore one of increasingly connected explanations, accompanied by a clearer recognition of their assumptions and limits. The geological record continued to generate new questions precisely because its detailed investigation could still challenge the larger reconstructions built from it.

Petrology, Mineralogy, Geochemistry and Geochronology: New Methods and Scientific Interpretations

Between 1993 and 2025, Czech petrology, mineralogy, geochemistry and geochronology became increasingly concerned with the different histories preserved within the same geological material. The composition of a rock remained essential, but it could no longer be treated as a sufficient account of its origin. A zircon core might survive from an older source, a garnet inclusion might retain evidence erased from the surrounding rock, and a secondary uranium mineral might record the chemistry of water passing through a former mine. The publications considered here suggest that the decisive development was the closer connection between analytical resolution and geological interpretation. Smaller analytical targets, better characterised reference materials and more explicit numerical models made it possible to ask more exacting questions about how the Earth’s crust had formed and changed.

This development drew upon established skills in field observation, petrography and mineral identification. Chemical measurements acquire geological meaning through the location of a sample, the relationships between its constituent minerals and the sequence in which those minerals formed. The studies discussed below repeatedly combine these forms of evidence. They also reveal a research community extending across Czech universities, the Czech Geological Survey, Academy institutes and museums, with substantial contributions made through laboratories abroad. Its history therefore includes both the development of analytical capacity within the Czech Republic and the work of Czech researchers in international partnerships. A national account would be incomplete if it confined scientific activity to the physical location of an instrument.

Research on the Central Bohemian Pluton illustrates the questions being reformulated during the first years of the independent state. In 1995, Vojtěch Janoušek, Graeme Rogers and Donald R. Bowes used strontium and neodymium isotopes to investigate the origins of its contrasting granitoid suites. Their interpretation did not reduce the observed variation to progressive

contamination of one parental magma. Different combinations of source composition, partial melting, magma interaction and crystallisation were considered for different suites. Particularly revealing was the possibility that a mantle contribution could possess an isotopically enriched signature. The work challenged any simple correspondence between a crust-like isotopic composition and an exclusively crustal source, while retaining several possible explanations where the evidence did not uniquely distinguish between them.

The subsequent study of this composite batholith, published in 2000 by Janoušek and colleagues, brought major elements, trace elements and isotopic compositions into quantitative petrogenetic models. The four principal suites required different explanations, including melting of contrasting source rocks, interaction between magmas and assimilation accompanying fractional crystallisation. These alternatives represented physically and chemically different histories, even where the resulting rocks shared a broad petrographic designation. This approach gave regional granite research a wider methodological purpose: a mapped pluton could be examined as a collection of related but distinguishable magmatic systems. It also showed why a successful chemical fit had to be assessed against mineral assemblages and geological relationships rather than accepted solely because a calculated trend passed through the observations.

The growing availability of analysis within individual minerals changed the scale at which such problems could be investigated. Jan Košler's 1999 account of laser ablation inductively coupled plasma mass spectrometry for uranium–lead zircon dating documents an early stage of this transition in the Czech research environment. A laser removed small amounts of material from selected positions, allowing isotopic measurements to be related more closely to the internal structure of a grain. The attraction was clear: older inherited components and later growth could potentially be examined separately. Yet the method required corrections for effects introduced during ablation and measurement. Its adoption was consequently an analytical development as well as an opportunity to generate additional dates.

Košler's collaboration with Michael Wiedenbeck, Richard Wirth, Jan Hovorka, Paul Sylvester and Jitka Míková addressed this difficulty directly in 2005. Their investigation examined the chemical and phase composition of particles produced by laser ablation of silicate glass and zircon, with particular attention to elemental fractionation during analysis. The analytical signal was thus treated as the outcome of a physical process whose products needed investigation. This contribution deserves a place beside geological applications because it concerns the reliability of the evidence on which those applications depend. Improving spatial resolution would have limited value if differences created during sample introduction were mistaken for differences originally present in a mineral.

The interpretation of mineral ages presented a related problem. A detailed 2004 study led by H. Timmermann, with Veronika Štědrá and other collaborators, investigated eclogites and associated rocks of the Mariánské Lázně Complex through geochemistry and uranium–lead analyses of several mineral species. Ages near 380 million years were interpreted in relation to exhumation and decompression melting rather than automatically assigned to the peak of high-pressure metamorphism. This was a substantive distinction: the age of a surviving or newly formed mineral need not identify the most extreme conditions experienced by its host

rock. The study exemplified the need to connect each isotopic result with a mineral's growth, reaction history and petrographic setting before using it to reconstruct a sequence of crustal events.

An especially tangible Czech contribution to analytical geochronology was the characterisation of zircon from Plešovice in southern Bohemia as a reference material. The international study published in 2008, led by Jiří Sláma and Jan Košler, compared measurements from several laboratories and techniques. It established a uranium–lead reference date of approximately 337 million years and evaluated the material for hafnium isotope microanalysis. Its suitability was specific: heterogeneity in trace-element concentrations prevented its straightforward use as a trace-element calibration standard, while radiation-damaged domains required avoidance. The achievement was therefore the careful definition of what a natural material could reliably support. A locality in the Bohemian Massif became a resource for making measurements comparable across laboratories, linking regional geological knowledge with the practical foundations of international research.

Increasing analytical throughput also encouraged scrutiny of the material selected for measurement. In their 2012 investigation, Sláma and Košler examined detrital zircon populations using a Scottish catchment and experimentally prepared sediments. They showed that source-rock zircon abundance, grain properties, separation procedures and the selection of crystals could alter the recovered age distribution. Small grains could be lost or under-represented before isotopic analysis began. For the history of Czech geochronology, this work demonstrates the contribution of researchers working through international appointments and field settings. It also established a useful interpretative caution: measuring more grains cannot by itself restore a population removed during sample preparation. Geological representativeness and instrumental precision are different qualities, both necessary for a credible reconstruction of sediment sources.

Metamorphic petrology was similarly transformed by attention to evidence preserved at particular positions within minerals. In 2010, S. W. Faryad, Radmila Nahodilová and David Dolejš examined inclusions in garnet from Moldanubian granulites. Their reconstruction identified evidence for an earlier stage of eclogite-facies metamorphism that had been modified during subsequent heating, partial melting and decompression. The interpretation depended partly on recognising the former presence of minerals through the shapes and reaction products of inclusions. A rock's most conspicuous present assemblage could therefore conceal an earlier history. This kind of work connected microscopic observations with changing pressure and temperature conditions, while making clear that preservation is selective: different domains within one specimen may retain different portions of its evolution.

Another strand of methodological renewal concerned the behaviour of fluids at depth. Dolejš and Craig E. Manning's 2010 thermodynamic model addressed mineral dissolution in aqueous fluids over an extensive range of temperatures and pressures. Calibrated against experimental solubility data, it linked mineral behaviour to the properties of the aqueous solvent and was applied to fluid transport and mineral precipitation. Its relevance extended from hydrothermal environments to metamorphic and subduction settings. For Czech research, the contribution illustrates how theoretical work could complement increasingly detailed analyses of natural

samples. Mineral associations and veins became objects that could be investigated through explicit calculations of dissolution, transport and precipitation, with the assumptions and calibration of the model forming part of the explanation.

Mineralogy followed a parallel course, combining long familiarity with individual localities and increasingly demanding structural and chemical characterisation. Jáchymov provided an outstanding example. During a project undertaken between 1993 and 1997, Petr Ondruš and collaborators investigated secondary phases from the ore district. Their 1997 publication described thirty inorganic phases encountered in nature for the first time, with characterisation necessarily varying according to the available material. This should not be read as a claim that thirty fully approved new mineral species were established in one paper. The work brought together chemical analysis, diffraction and, for selected phases, crystal-structure determination or refinement. It demonstrated how renewed examination of a historically celebrated district could reveal mineralogical relationships that older descriptions and collections had not resolved.

The pegmatite research associated with Milan Novák offered a different form of synthesis. His substantial Czech-language study of 2005 organised the granitic pegmatites of the Bohemian Massif through mineralogical, geochemical and regional classification, explicitly considering their geological significance. The value of such a synthesis lay in connecting detailed local observations with categories that could support comparison between occurrences. Pegmatites were treated as products of geological histories whose mineral assemblages and chemical characteristics required explanation. Within the development of Czech mineralogical research, this work provided a framework through which a large regional body of knowledge could enter broader discussion without losing the distinctions between particular geological settings.

Jan Cempírek and Novák's 2006 investigation of dumortierite-bearing pegmatites at Starkoč and Běstvina illustrates the interpretative detail behind that regional perspective. At Starkoč, their study distinguished primary igneous, prograde metamorphic and retrograde mineral assemblages. Changes in tourmaline composition helped reveal the influence of metamorphism and interaction with the host rock. A mineral present in a pegmatite could consequently belong to more than one stage of its development. This finding connected mineral chemistry with the order of geological processes and with the environment surrounding the vein. It also explains why mineral identification alone was insufficient: the same mineral name could encompass compositions and generations that carried different historical information.

Research on uranium minerals developed particularly strong connections between descriptive mineralogy, crystal chemistry and geochemical processes. Jakub Plášil's 2014 review of uraninite oxidation and hydration considered the transformation of the primary mineral into secondary uranyl phases. These transformations depend on both the composition of the starting material and the chemical conditions of the reacting fluids. Understanding the resulting assemblages required attention to crystal structures and to the stability of the products. The review shows how a field with deep historical roots in Czech mining districts acquired renewed explanatory scope. Secondary minerals could be studied as records of

reactions and chemical conditions, bringing the description of a specimen into contact with the movement and retention of elements during weathering.

The same year's study of the Červená vein at Jáchymov, by Plášil, Jiří Sejkora, Radek Škoda and Pavel Škácha, made that connection concrete. Their investigation related recent uraninite alteration to the geochemical characteristics of the primary mineralisation and to the changing alteration assemblage. Structural information and a bond-valence approach helped interpret the observed minerals, while the influence of copper and rare-earth elements linked the secondary products to their sources. The case demonstrates a continuity of scientific purpose across analytical scales. The identity and structure of very small crystals were relevant to understanding the evolution of an entire weathering association. It also showed that local mineralogical detail could test explanations of how geological materials respond to changing chemical conditions.

Environmental geochemistry extended isotopic investigation towards processes operating at the Earth's surface and within landscapes modified by human activity. Michael Komárek, Vojtěch Ettler, Vladislav Chrastný and Martin Mihaljevič's 2008 review of lead isotopes examined their use in distinguishing sources of environmental lead, alongside the analytical methods on which such investigations relied. Source tracing brought isotope geochemistry into contact with emissions, industrial materials and environmental transport. The methodological link with petrology was substantial: in both settings, a measured composition had to be interpreted through mixing, source variability and subsequent change. This extension broadened the range of questions addressed by Czech geochemists while retaining the need to establish whether the proposed sources were chemically and isotopically distinguishable.

By the end of the period, the analytical infrastructure supported a much broader combination of measurements. The Czech Geological Survey's report for 2024 documents thermal ionisation and multicollector plasma mass spectrometry, laser ablation, zircon geochronology and hafnium isotope analysis, alongside diffraction and electron microscopy. It also records continuing development of chemical separation and measurement procedures, including work on iron isotopes in rocks. These capabilities should not be projected backwards onto the early 1990s. They indicate the scale of analytical integration reached during the intervening decades. Equally significant is the report's treatment of sample preparation and method development as continuing scientific work. An instrument list alone cannot convey the expertise required to produce reliable results from different materials.

The management and interpretation of chemical data constituted another area of Czech methodological contribution. In 2006, Janoušek, Colin M. Farrow and Vojtěch Erban introduced the Geochemical Data Toolkit, usually known as GCDkit, in the *Journal of Petrology*. Built around the R computing environment, it brought the handling and graphical interpretation of whole-rock geochemical data into a shared software framework. Its importance for the present history is that computational practice became an identifiable research output. The procedures used to organise and examine measurements could be developed and communicated alongside the geological findings. Such tools also created a connection between specialists undertaking quantitative analysis and geologists needing a practical route into the interpretation of compositional datasets.

The 2016 book *Geochemical Modelling of Igneous Processes*, written by Janoušek, Jean-François Moyen, Hervé Martin, Erban and Farrow, developed this quantitative approach through worked examples in R. It addressed partial melting, fractional crystallisation, magma mixing and assimilation, including the use of radiogenic isotope information. The educational contribution was closely connected to research practice: a model could be explored by changing its inputs and examining the consequences. This made the assumptions behind a proposed petrogenetic history more accessible to inspection. A calculation could constrain an explanation without uniquely proving it, since several combinations of sources and processes might yield similar compositions. The book's combination of principles and practical implementation helped make that distinction part of the learning process.

The computational strand continued to develop during the final years covered here. In 2024, Janoušek, Farrow and Erban presented GCDkit.Mineral for the recalculation, plotting and classification of electron probe analyses of common rock-forming minerals. This moved the shared computational approach from whole-rock datasets towards mineral compositions. Recalculation is a consequential step because measured elemental abundances must be expressed in forms suitable for structural formulae and mineral classification. By making the relevant procedures configurable within an R-based environment, the software linked routine analytical work with explicit choices about calculation and nomenclature. Its publication also demonstrates that the interpretation of laboratory results remained an area of methodological development even after many analytical techniques had become established.

Janoušek's HafAn script, also published in 2024, addressed the interpretation of hafnium isotopic data from whole rocks and individual zircon domains. It supported calculations and graphical examination of isotopic evolution, including model ages. This application brought geochronology and source interpretation into particularly close contact. The measured crystallisation age of a zircon and a model age inferred from its hafnium composition answer different questions; the latter depends on an assumed history of isotopic evolution. Making these calculations available within a documented computational approach helped expose the relationship between an analytical result and its interpretative framework. It also reinforced a lesson running through the period: increased numerical detail is most useful when the assumptions accompanying it remain visible.

A study published in 2025 by Janoušek, Tomáš Magna and collaborators shows that interpretation remained open to revision at the close of the period. Their investigation of potassic and ultrapotassic rocks of the Moldanubian Zone used stable isotope evidence to consider how mantle-derived magmas could acquire strongly crust-like characteristics. They argued that crustal material transferred into the mantle through melts or fluids could obscure a mantle contribution in some geochemical indicators. On this basis, they proposed a distinction between reworking within the crust and reworking involving the mantle beneath it. These terms express the authors' interpretation rather than an agreed replacement for existing terminology. The broader implication was that isotope maps and simple divisions between juvenile additions and recycled crust needed to be evaluated against the processes capable of modifying a source before magma formation.

Taken together, these studies suggest that the development of the four fields cannot be measured simply by the number of new analytical techniques introduced. Progress also lay in identifying what each technique could resolve, which geological event a result represented and which parts of a sample's history remained inaccessible. The growing use of microanalysis, reference materials, structural mineralogy and numerical modelling created opportunities for more discriminating interpretations. It also made disagreement more specific: alternative explanations could concern a source component, a mineral generation, a separation bias or an assumption in a calculation. For researchers and students, learning to distinguish these levels of uncertainty became an essential part of interpreting increasingly elaborate datasets.

By 2025, the selected Czech contributions formed a connected body of work extending from the internal arrangement of atoms in secondary minerals to the sources and evolution of crustal magmas. Their international reach rested on several forms of achievement: detailed studies of Czech localities, collaboration across laboratories, reference materials that supported comparison, and computational resources that made quantitative reasoning more accessible. The enduring intellectual thread was the relationship between observation and explanation. A finer measurement could reveal an older history, overturn an apparently straightforward source assignment or show that a familiar mineral belonged to an unexpected stage of development. The strongest interpretations emerged where those measurements remained anchored in the geological circumstances that had produced and preserved them.

Stratigraphy, Palaeontology and Sedimentary Geology: Reconstructing Geological Time and Past Environments

During the period from 1993 to 2025, Czech stratigraphy, palaeontology and sedimentary geology became more closely connected through the reconstruction of geological time and environmental change. Established fossil successions and carefully described rock sections remained indispensable, while chemical records, geophysical measurements, numerical analysis and 3D imaging enlarged the questions that could be asked of them. The resulting studies examined the duration of events, the relationships between changing environments and biological communities, and the extent to which a local succession represented processes operating elsewhere. The examples considered here show a sustained development of regional expertise into research with international relevance, accompanied by closer scrutiny of how geological evidence had been deposited, preserved and subsequently altered.

The independent Czech Republic inherited a substantial responsibility for international stratigraphic reference sections. At Klonk, near Suchomasty, the boundary between the Silurian and Devonian systems had already been defined before 1993. It is located within a particular bed in a succession of limestones and calcareous shales and is tied to the appearance of an index graptolite. Such a Global Boundary Stratotype Section and Point, generally abbreviated to GSSP, defines a physical reference for a boundary in geological time. Its existence does not make every correlation straightforward. Researchers must still establish

how the reference level can be recognised in rocks deposited under different conditions and whether a distant section contains a complete record of the relevant interval.

Detailed palaeontological work continued to refine this inherited framework during the 1990s. Petr Štorch's 1994 investigation of the Llandovery–Wenlock boundary interval examined graptolite-bearing sections bed by bed, including temporary excavations at Velká Ohrada. It combined descriptions of assemblages with taxonomic revision and comparison of biozones. The observed faunal change did not have the same expression at every nominal zonal boundary, and correlation required attention to the presence or absence of particular zones in other regions. This work illustrates why systematic palaeontology remained integral to stratigraphic progress. The identification of a fossil, its range within a section and the reliability of comparisons with older descriptions all affected the temporal framework within which sedimentary change could be interpreted.

Regional synthesis also retained an important place. The English-language monograph *Palaeozoic of the Barrandian*, published in 1998 by Ivo Chlupáč, Vladimír Havlíček, Jiří Kříž, Zdeněk Kukal and Štorch, brought the Cambrian to Devonian succession into a single substantial work. Its publication belongs to the same period as the increasingly international circulation of Czech geological research. It provided a common regional reference for specialists approaching the Barrandian from different palaeontological and geological perspectives. The continuity expressed by such a synthesis matters when assessing developments after 1993: new measurements were applied to formations, localities and fossil groups whose identities had been established through a much longer history of investigation.

The subsequent methodological changes made the distinction between rock succession and elapsed time increasingly explicit. Lithostratigraphy describes and correlates bodies of rock, whereas biostratigraphy uses the distribution of fossils. Neither a change in rock type nor the disappearance of a species necessarily marks a synchronous event throughout a basin. Sediment supply, water depth and ecological preferences can move the position of an apparent boundary. The Czech studies discussed below addressed these problems by bringing different records into the same stratigraphic framework. Agreement between independent observations strengthened a correlation; disagreement could reveal an ecological change, a gap in deposition or alteration after burial. Such discrepancies became useful geological evidence in their right.

Research on the late Silurian carbon cycle exemplifies this approach. Jiří Frýda and Štěpán Manda's 2013 investigation of the mid-Ludfordian carbon isotope excursion combined its geochemical record with graptolite and conodont stratigraphy. Their study documented a prolonged interval of relatively stable, isotopically heavy carbon following the initial rise. The form of the excursion therefore mattered alongside its maximum value. Its relationship to fossil zones allowed a chemical pattern to be placed within a biological chronology and compared with records from other palaeogeographical settings. For the development of Czech research, this was a consequential extension of the traditional study of Silurian faunas: the same successions could contribute to questions about ocean chemistry and the timing of environmental disturbance.

František Vacek, Ladislav Slavík, Katarzyna Sobień and Pavel Čáp's 2018 study of the Požáry section combined sedimentology, gamma-ray spectrometry and conodont biostratigraphy. The succession included the Přídolí GSSP and extended from the latest Ludlow into the earliest Devonian. Changes from more distal carbonate deposits to shallower bioclastic facies were interpreted within a transgressive–regressive sequence. The authors related the overall pattern principally to sea-level change while allowing a temporary influence from local tectonics. This combination of evidence made the reference section informative about the environment in which its strata accumulated. A boundary locality could thus support both the ordering of geological time and an explanation of the processes that shaped its physical record.

Even intensively investigated fossil localities continued to yield information late in the period. A study published in December 2025 by Zuzana Strossová, Carlo Corradini and Maria G. Corriga documented conodonts together with graptolites in Telychian black shales at Želkovice. The locality had long been known for exceptionally preserved graptolites, but conodonts had not previously been recorded there. Their co-occurrence provided a direct connection between fossil groups whose differing environmental distributions often complicate correlation. The authors also examined the ecological implications of the assemblage. The case shows that refinement could arise from renewed collecting and identification at a familiar section, as well as from the introduction of a new analytical instrument.

The Bohemian Cretaceous Basin provided another setting in which chronology and environmental reconstruction developed together. In 1997, David Uličný and collaborators examined sea-level changes and geochemical anomalies across the Cenomanian–Turonian interval at Pecínov. Their interpretation connected the sedimentary succession with changing bottom-water oxygenation and a carbon isotope excursion. The relationship was more complex than an association between the highest sea level and the strongest oxygen depletion. The authors considered the development of transgression and the changing contribution of organic matter when interpreting the chemical record. This early post-1993 example already treated environmental events as sequences of interacting processes, demonstrating that chemical anomalies needed to be read within the architecture and depositional history of the section.

By 2009, Uličný, Jiří Laurin and Stanislav Čech were investigating the geometry of sedimentary sequences across the basin through the combination of borehole logs, exposures and biostratigraphy. Their study distinguished the effects of faulting, subsidence, sediment supply and sea-level fluctuations on deltaic and offshore deposits. These controls varied through time and between parts of the basin. A thick succession could reflect the creation of additional space for sediment rather than a longer interval of time, while a shoreline could advance through increased sediment input as well as falling relative sea level. The research placed individual sections within a 3D regional interpretation. It thereby supplied a stronger basis for deciding which sedimentary patterns might reflect wider environmental change.

International correlation became particularly effective when this regional framework was combined with closely sampled geochemistry. A study published in 2015 by Ian Jarvis, João Trabucho-Alexandre, Darren R. Gröcke, Uličný and Laurin compared carbon isotope records

from organic matter and carbonate in the Bch-1 research core at Běchary. The core, drilled in 2010, sampled a 405-metre succession extending from the uppermost Cenomanian into the Lower Coniacian. Its records could be compared with coeval successions in Europe, North America and Japan. The study nevertheless retained biostratigraphic control as essential and identified limitations imposed by diagenetic alteration of carbonate. The resulting correlations were strengthened by examining preservation and comparing different materials, rather than assuming that every measured chemical fluctuation was an unchanged signal from ancient seawater.

Astronomical calibration added a further dimension to this work. In 2021, Laurin and colleagues used laterally consistent sedimentary cycles, ammonite biozones and carbon isotope data to refine the chronology of the Early Turonian. Variations in the expression of precession cycles were related to longer eccentricity cycles, allowing the authors to estimate an Early Turonian duration of approximately 885,000 years, with a reported uncertainty of 41,000 years at two standard deviations. This kind of result addressed the tempo of geological change as well as the relative ordering of events. It required evidence that the cyclic signal could be traced between sections and distinguished from local variations in sedimentation. The study also explored a possible astronomical influence on recovery from the Cenomanian–Turonian oceanic anoxic event, presenting a mechanism for investigation rather than a simple equivalence between cyclicity and causation.

Čech and Uličný's 2021 study of the Turonian–Coniacian boundary addressed correlation across contrasting sedimentary environments. They connected detailed fossil successions with sequence stratigraphy and carbon isotope records in deltaic through offshore deposits. The Czech succession could then be compared with the well-studied sections at Salzgitter-Salder in Germany and Słupia Nadbrzeżna in Poland. Its expanded record complemented those localities while preserving evidence from a setting with substantial input of terrigenous sediment. This illustrates a distinctive contribution of basin research to international stratigraphy. A section becomes valuable through the particular interval and depositional setting it preserves, and through the demonstrable connections that allow it to clarify records elsewhere.

Reconstruction of Cretaceous environments also benefited from closer collaboration between palaeobotanists and sedimentary geologists. Jiří Kvaček and a substantial team of collaborators published a synthesis in 2024 of five terrestrial environments represented in the Cenomanian Peruc–Korycany Formation. Plant remains of different sizes, pollen, sedimentology and geochemical evidence were considered together. The reconstructed settings ranged from saltmarshes and coastal freshwater swamps to river floodplains and drier uplands. Angiosperms were particularly diverse in the alluvial environments, whereas conifers remained prominent in the more environmentally stressful coastal settings. The interpretation related the expansion of flowering plants to differences between habitats. It consequently gave a more discriminating account of ecological change than a single inventory of the regional flora could provide.

Plant fossils also carried information about the circumstances of preservation. Leaves transported into a channel, pollen dispersed over a wider area and vegetation buried where it

grew represent different samples of an ancient landscape. Their agreement cannot be assumed merely because they occur within the same formation. The combination of palaeobotanical evidence with sedimentary setting made these differences central to environmental reconstruction. In this respect, research on fossil vegetation developed in parallel with marine biostratigraphy: both required an understanding of how organisms entered the geological record. An assemblage could indicate the age of a deposit, the environment in which its source organisms lived, or the processes that concentrated their remains, with different evidence needed to distinguish those possibilities.

The Pennsylvanian coal basins offered unusually direct opportunities to investigate former ecosystems. In 2009, Stanislav Opluštil, Josef Pšenička, Milan Libertín and collaborators described a peat-forming forest buried in volcanic ash in the Whetstone Horizon of the Radnice Basin. Excavation exposed plant remains in their original spatial relationships, allowing the community to be reconstructed through its growth forms and vertical organisation. The ash burial preserved an ecological snapshot that differed from the mixed and transported material commonly encountered in sedimentary deposits. The investigation connected systematic palaeobotany with the physical reconstruction of a mire. Its spatial limits remained those of the excavated area and the particular community preserved, but within those limits it provided unusually detailed evidence of how a Carboniferous forest had been organised.

Volcanic ash beds also helped connect terrestrial fossil successions with numerical geological time. Opluštil, Mark Schmitz, Christopher J. Cleal and Karel Martínek's 2016 review used fifteen new high-precision uranium–lead zircon ages from continental basins of central and western Czechia. These dates improved the calibration of regional Pennsylvanian substages and their correlation with the international time scale. They also tested correlations based on fossil plants and terrestrial or freshwater faunas against the marine framework. Most floral biozones were supported as approximately synchronous, although the ranges of individual taxa could differ between basins. Here, geochronology strengthened palaeontological classification while identifying the limits of particular markers. The dating methods discussed in the preceding section thus acquired a direct role in reconstructing sedimentary and biological history.

Research in Moravia placed comparable questions within a younger marine basin. Slavomír Nehyba and Jan Šikula's 2007 analysis of the Carpathian Foredeep recognised five principal depositional sequences within its Neogene fill. Their interpretation related changes in basin geometry and sedimentary architecture to the interaction of tectonics, sea level, sediment supply and the relief of the underlying surface. The relative influence of these factors changed as the basin evolved. Sequence stratigraphy supplied a way to examine those changing controls through the arrangement of deposits and their bounding surfaces. The study also extended Czech sedimentary research beyond the geological settings most closely associated with the Barrandian tradition, connecting Moravian observations with the development of the Carpathian foreland system.

Non-marine deposits presented a further challenge where conspicuous fossils were scarce. Tomáš Matys Grygar, Karel Mach, Petr Schnabl, Petr Pruner, Laurin and Mathieu Martinez's 2014 investigation of the Most Basin examined a thick Early Miocene lake succession largely lacking macrofossils. Magnetostratigraphy and sedimentary cyclicity helped establish an age

model for the lake record, placing it approximately between 17.4 and 16.6 million years ago and across the onset of the Miocene Climatic Optimum. The recognition of orbital rhythms supported interpretation of the succession as a persistent lacustrine archive. This work broadened the material available for environmental history. Fine-grained sediments whose appearance offered few obvious chronological clues could preserve a useful record when investigated through complementary physical and geochemical properties.

These basin studies made the scale of observation an increasingly explicit part of interpretation. A single outcrop might show a local environmental transition, while correlation across a basin could establish whether the change was widespread or restricted to one depositional setting. A dated ash bed supplied a numerical anchor; a fossil succession provided ordering between anchors; sedimentary cycles could help assess the time represented within an interval. Their combination did not remove gaps or automatically identify the cause of environmental change. It made those questions more tractable by showing which observations were independent and which conclusions depended on the same underlying assumption about sedimentation or correlation.

Palaeontology also developed new ways of examining the organisms themselves. In 2020, Valéria Vaškaninová, Donglei Chen and an international team used synchrotron microtomography to investigate tooth-bearing structures in Early Devonian fishes from the Czech Republic. The genera studied included *Radotina*, *Kosoraspis* and *Tlamaspis*. Internal anatomy revealed marginal dentitions and patterns of tooth addition that the authors proposed as ancestral characteristics of jawed vertebrates. The contribution rested on the conjunction of Czech fossil material, specialist anatomical knowledge and access to imaging facilities abroad. It showed how evidence from a well-established geological region could inform an evolutionary question extending far beyond regional stratigraphy, while allowing anatomical structures to be reconstructed without relying solely on exposed specimen surfaces.

A related development was the investigation of preserved biological interactions. Petr Kraft, Vaškaninová, Michal Mergl, Petr Budil, Oldřich Fatka and Per E. Ahlberg's 2023 study examined the gut contents of the Ordovician trilobite *Bohemolichas incola*. The specimen came from the Šárka Formation of the Prague Basin and was preserved in a siliceous nodule. Synchrotron microtomography at Grenoble revealed an extensive gut fill containing partly fragmented calcareous shells. Their preservation allowed the authors to discuss feeding intensity and infer aspects of the digestive environment. The conclusions went beyond assigning the animal a presumed ecological role from its external shape. They drew on direct evidence of ingested material, interpreted within the circumstances that had preserved it inside the fossil.

The two imaging studies illustrate a change in the research value of collections and newly collected specimens. A fossil's internal structure could become accessible long after the enclosing rock and the organism's general identity were familiar. At the same time, a 3D reconstruction required choices about distinguishing structures within the scan and relating them to comparative anatomy or preservation. Digital models enlarged access to evidence, but the geological position and physical specimen continued to matter. The connection with sedimentary geology remained close: exceptional preservation was itself a product of the environment, burial history and subsequent transformations of the enclosing material.

By the final years of the period, international participation encompassed the revision of stratigraphic standards as well as collaborative research on individual successions. The Czech Geological Survey's account of its 2024 activities records work on a replacement Telychian GSSP in southern Spain and the submission of a proposal to subdivide the Přídolí Series. This work connected palaeontological expertise with the formal evaluation of reference sections and proposed boundaries. The same report describes continued research on marine ecosystems, fossil plants and sedimentary records. Such activity indicates that the Czech contribution involved both maintaining knowledge of domestic reference sections and contributing expertise to the wider organisation and interpretation of geological time.

Viewed across the whole period, the development was cumulative. During the 1990s, taxonomic revision, regional synthesis and integrated studies of particular sections already supported international comparison. Work during the following decades increasingly placed those sections within basin-wide frameworks and coupled fossil successions with chemical records and numerical ages. By the 2010s and early 2020s, astronomical calibration and internal imaging of fossils had added further kinds of evidence. These approaches continued alongside detailed field description and systematic palaeontology. Their productive use depended on recognising precisely what each record represented, whether a biological range, a depositional episode, an orbital rhythm or a structure preserved within one organism.

For researchers and students, this history offers a practical account of how reconstructions become more persuasive. Geological time is established through reference points and correlations that must work across different environments. Ancient environments are reconstructed from evidence affected by transport, burial, ecological selection and later alteration. Czech research between 1993 and 2025 repeatedly brought those two problems together. Its strongest examples made the relationship between a specimen, a measured section and a larger temporal framework explicit. The result was a more detailed account of past life and landscapes, with clearer grounds for deciding which features were local, which could be correlated widely, and how securely their sequence and duration were known.

Strengths, Uneven Development, Institutional Challenges and the Training of New Researchers

The development of Czech geological sciences between 1993 and 2025 produced a research system whose achievements rested on specialised expertise and sustained collaboration. Its strengths were particularly evident where detailed knowledge of rocks, minerals and fossils could be combined with analytical methods or used to address questions of wider geological significance. The record also reveals differences in the resources and institutional arrangements supporting individual fields. Preserving a successful research tradition required more than continued publication: it depended on maintaining access to specimens, observations and laboratories, and on preparing researchers capable of questioning the interpretations they inherited. This concluding section examines those relationships through

scientific contributions, institutional documents and evidence concerning the training of new researchers.

Institutional continuity helped make this development possible. The Institute of Geology's published history records its re-establishment in 1990 following earlier mergers and organisational changes, and describes the range of geological specialisms subsequently pursued. Established subjects and specialist knowledge continued to provide a basis for research after the creation of the independent Czech state. The history after 1993 should therefore be understood through the adaptation of an existing community. The preservation of expertise was an achievement, but continuity also placed a responsibility on institutions to ensure that knowledge held by experienced researchers could become accessible to their successors.

One scientific strength was the ability to connect intensive regional investigation with explanations of crustal evolution. The Bohemian Massif provided the material for studies in which structural observations, petrology and geochemical information could be assessed together. The interpretation of Palaeozoic convergence advanced by Karel Schulmann and collaborators in 2009 illustrates the scale of questions that such work could address. Its relevance extended beyond the description of Czech geological units to the construction and testing of models for an ancient orogenic system. The enduring asset was the connection between a closely studied region and methods capable of placing that region within a larger geological history. Alternative interpretations could be tested against increasingly detailed observations.

Mineralogy demonstrated a comparable capacity to renew a longstanding specialism. Jakub Plášil's work on uraninite weathering connected mineral associations with crystal structures, fluid chemistry and the stability of alteration products. Local knowledge of uranium mineral occurrences could consequently contribute to understanding how elements changed form and were redistributed during weathering. This relationship between systematic mineralogy and geochemical processes gave an established field continuing scientific relevance. It also underlines a particular requirement of specialised research: progress depends on the ability to identify small or uncommon phases reliably, preserve their geological context and interpret their structures. Those skills are difficult to replace through an instrument purchase alone.

Some Czech contributions became resources for the wider scientific community. The 2008 characterisation of Plešovice zircon as a reference material for uranium–lead and hafnium isotope microanalysis is a clear example. Its value depended on careful interlaboratory investigation and a defined understanding of the material's suitability and limitations. Such work helped other laboratories assess the comparability of their measurements. It represents a form of scientific strength that publication counts alone describe incompletely: the contribution enters the procedures through which further research is undertaken. Regional geological material acquired international methodological importance because researchers established what could be measured reliably and made that knowledge available to others.

The geographical position of the country did not confine its scientific questions to present-day terrestrial environments. Research on the Bohemian Cretaceous Basin contributed to marine

stratigraphy and the reconstruction of ancient seas. Stanislav Čech and David Uličný's investigation of the Turonian–Coniacian boundary linked Czech deltaic and offshore successions with sections in Germany and Poland. The example shows why the strength of a geological field cannot be inferred directly from the country's modern physical geography. Preserved geological records and the expertise used to interpret them can sustain research on environments that no longer exist locally. The relevant distinction concerns access to suitable evidence and methods, rather than proximity to a modern coastline.

Uneven development was partly a matter of specialisation. Research on the Carpathian Foredeep by Slavomír Nehyba and Jan Šikula illustrates the importance of Moravian sedimentary basins for sequence stratigraphy and basin analysis. In Ostrava, the Institute of Geonics documented research in geomaterials, geomechanics and computational approaches to problems involving rock masses. These activities addressed different geological materials and different kinds of scientific or practical question. Their coexistence strengthened the national system by providing complementary expertise. It also meant that the same facilities, supervisory experience and research opportunities were not available in identical form at every institution. Collaboration could bridge these differences without removing the need for local competence.

Specialisation has consequences for succession. A productive field may depend on a small group able to recognise a particular fossil assemblage, operate an analytical method or interpret a distinctive geological setting. The departure of one experienced researcher can then affect a broader set of projects and training opportunities. This is an organisational implication of the specialised work considered in this chapter, rather than evidence that all Czech geological fields experienced the same staffing problem. A useful assessment of uneven development must therefore consider the continuity of expertise alongside visible research outputs. A subject's place in a curriculum does not, by itself, establish the depth of the research community supporting it.

The Czech Geological Survey's research concept for 2023–2027 shows how different scientific responsibilities were brought together within a public institution. Its programme encompassed crustal structure and dynamics, the sedimentary record and biosphere, mineral resources, groundwater, geoenergy, geohazards and landscape biogeochemistry. Institutional support for this framework existed alongside nationally and internationally funded projects. The arrangement created connections between fundamental investigation and questions arising from public administration or resource use. It also required the organisation to accommodate work with different timescales and products. Geological information needed for a public decision, a maintained dataset and a research article could all draw on the same specialist knowledge while serving different purposes.

Long-term documentation was one of the less conspicuous strengths supporting these activities. The Survey's account of 2024 describes continuing preservation of drill cores, geological samples and unpublished reports, together with their progressive digitisation. Their scientific value depended on preserving the link between a physical sample and its recorded origin. For training, this provided an opportunity to work with geological evidence whose

acquisition could not readily be repeated. Maintaining such material constituted a continuing institutional task, extending beyond the duration of the project that originally produced it.

The analytical infrastructure presented a similar relationship between achievement and obligation. The Plešovice study demonstrated why a reference material's suitability had to be established for particular uses. Infrastructure includes the expertise needed to recognise unsuitable domains, diagnose unexpected results and maintain comparability between measurements. Training a researcher to submit a specimen for analysis is consequently a more limited undertaking than training someone to judge the resulting evidence. A durable analytical capability requires both access to equipment and opportunities to acquire that judgement.

Competitive funding became an established part of the research environment. The Czech Science Foundation's Standard Projects scheme had operated since 1993, and its announcement of projects beginning in 2025 showed the continuing importance of this route. The same announcement distinguished schemes for international postdoctoral experience, independent early-career research and more ambitious projects by established investigators. These opportunities supported different stages of a scientific career. Their competitive character also meant that an institution had to plan across more than one source of support. A grant could enable a new direction or collaboration, but the continued availability of the expertise and facilities involved required decisions extending beyond the individual award.

Research evaluation also became more explicit about the conditions supporting scientific work. Methodology 2017+, approved in 2017 and published in the English edition consulted here in 2018, combined assessment of research results with social relevance, organisational viability and strategy. For geological institutions, these distinctions were consequential. A research paper, an expert contribution to a public decision and the maintenance of an effective research environment called for different kinds of assessment. The framework offered a basis for examining those responsibilities together. Its existence did not settle every question of value, but it recognised that the quality of an organisation could not be represented adequately by treating every activity as an interchangeable unit of publication.

The Academy's methodology for evaluating the period 2015–2019 similarly specified informed peer review, field-sensitive assessment and consideration of institutes and their research teams. It combined selected outputs, bibliometric information and institutional accounts with international expert evaluation. For a community containing highly specialised geological subjects, attention to field differences was especially relevant. It permitted assessment to ask what a team had contributed within its research setting and what conditions supported its future work. These provisions should be read as the design of an evaluation process. They do not establish that every geological team achieved the same quality or had equivalent prospects, questions requiring the results of individual assessments.

Institutional reports provide concrete evidence of financial constraints towards the end of the period. The Institute of Geology's report for 2024 described inflation, limited budget increases and reduced grant support as difficulties for staff renewal and competitive recruitment. It warned that the prevailing conditions severely restricted the recruitment of leading researchers

from abroad. This institutional assessment identifies a mechanism by which scientific strength could become difficult to sustain. The capacity to undertake internationally relevant work did not automatically provide the resources needed to recruit its next generation.

The Institute of Geonics reported a related problem in 2024. A small nominal increase in institutional support had not offset the effects of inflation, leaving additional grants and contract research important to its financial position. Its report also noted the substantial staff capacity absorbed by preparing project applications. Taken together with the Institute of Geology's account, this supports a qualified assessment of resource pressures in particular parts of the system. The challenge involved the purchasing power of funding and the research time needed to secure it. Continued scientific activity and success in some competitions could coexist with pressure on the conditions under which that activity was maintained.

These pressures mattered for doctoral research because a dissertation requires a coherent sequence of work. Field sampling, laboratory preparation, measurement, interpretation and publication may depend on different people or funding arrangements. Interrupting one part can delay the others. The relevant planning task is to establish which facilities, specialist assistance and resources a project can rely upon throughout that sequence. A strong scientific question is essential, but its feasibility also depends on those commitments. This is particularly evident in geology, where access to a locality may be seasonal, specimens can require lengthy preparation and analytical decisions are often revised after the first results become available.

The training system joined universities with research organisations that supplied supervision and specialist environments. The Institute of Geology's 2024 report records staff participation in university teaching, practical courses, dissertation supervision and doctoral boards. Its role extended beyond hosting occasional measurements. Such arrangements enabled students to encounter research practices and expertise distributed across institutions. They also created shared responsibilities: the university's degree requirements had to remain compatible with the project and laboratory conditions under which the student worked. The effectiveness of this cooperation depended on an intelligible division of supervisory, academic and practical support.

Masaryk University's published guidance for its Geology doctorate illustrates the breadth of these expectations. It links individual study plans with literature review, specialist seminars, teaching experience, publication and international activity. Annual assessment is part of the framework, and the spring 2025 course catalogue separately records the annual report and presentation at an international conference. These documents describe training as sustained participation in scientific work. Their significance lies in the connection between producing a dissertation and acquiring the ability to explain research to others, assess relevant literature and revise a programme of work. Requirements on paper still depend on supervision that helps the student make those activities intellectually useful.

Methodological education was particularly important where the volume of analytical data increased. Jiří Sláma and Jan Košler's investigation of detrital zircon studies showed how sampling and mineral separation could change an observed age distribution before the

measurement itself. For a new researcher, this is a practical lesson in the difference between analytical precision and geological representativeness. The skills needed include judging how samples were selected, recognising what preparation may have removed and deciding whether the surviving material can answer the original question. Technical training becomes research training when the student can explain those choices and their consequences, including cases where an apparently precise result supports only a limited interpretation.

Quantitative modelling introduced comparable demands. The 2016 book *Geochemical Modelling of Igneous Processes*, by Vojtěch Janoušek and collaborators, connected petrogenetic principles with calculations and worked examples in R. It offered a resource through which researchers could explore how assumptions about melting, crystallisation or mixing affected the predicted composition of rocks. Its relevance to training extends beyond learning a computing language. A student must understand why particular parameters were chosen and whether other combinations could reproduce similar observations. The acquisition of computational skill is most valuable when it strengthens that reasoning and enables another researcher to inspect or repeat the calculation.

International collaboration enlarged the environments in which such learning could take place. The 2023 investigation of preserved trilobite gut contents by Petr Kraft, Valéria Vaškaninová and colleagues combined Czech fossil expertise with synchrotron imaging at Grenoble and international interpretation. The example demonstrates how access to a specialised facility could become part of a wider research process involving specimen selection, image reconstruction and biological explanation. It also shows why international experience cannot be reduced to travel alone. Its educational value depends on participation in the decisions that connect a measurement to a scientific conclusion. The useful outcome is expertise that a researcher can subsequently apply, explain and develop within further collaborations.

Knowledge transfer also took place through organised mentoring. The Czech Geological Survey reported seven mentor–mentee pairs in 2024, working on geological and geomorphological mapping, exploration, analytical methods and scientific publication. This gave an explicit institutional form to learning from experienced colleagues. In geological work, a judgement made in the field or during specimen selection may otherwise remain difficult to reconstruct from a finished article. Mentoring can expose the observations and decisions behind that judgement. Its value therefore includes passing on practical competence while giving less experienced researchers the opportunity to question and eventually exercise it independently.

Doctoral financing underwent a significant change in 2025. Masaryk University’s Faculty of Science newsletter described the introduction of guaranteed doctoral study income for eligible full-time students within the standard study period. The new arrangement could combine a scholarship with countable wages for work related to the dissertation. The university also set out its intention to extend the guarantee to qualifying students already enrolled. These conditions matter when interpreting the reform historically: it changed the relationship between financial support and doctoral research, rather than making every doctoral student an employee on identical terms. For geology, it formed part of the wider university environment within which research projects and admissions had to be planned.

The institutional implications were discussed explicitly by Luděk Bláha, the Faculty's vice-dean for doctoral studies, in February 2025. He connected better financial support with the need to match admissions to available funding and supervisory capacity. This was a faculty-wide assessment, and it does not demonstrate a measured fall in geology enrolments. It does, however, identify a relevant tension for specialised programmes. Supporting doctoral researchers adequately can require more selective decisions about how many projects an institution can sustain. A small field must then consider how to preserve continuity without admitting students to work that lacks the resources or supervision needed for completion.

By the closing years of the period, research competence also increasingly included the management and reuse of data. The EPOS strategy for 2024–2028, in its 2025 version, placed shared standards, interoperable services and sustained access at the centre of European solid Earth infrastructure. This provides a useful context for assessing the demands on geological institutions and their trainees. Making data available requires documentation of provenance, methods and uncertainty, alongside the technical means of storing and retrieving them. These tasks have educational value when they allow students to understand how a dataset was produced and whether it can support a different question. They also require continuing institutional attention after a particular publication has appeared.

Across 1993–2025, the strongest Czech geological contributions combined inherited knowledge with methods that made new interpretations possible. The same combination explains several of the system's vulnerabilities. Specialisation increases the value of experienced researchers, analytical progress requires continuing technical competence, and international participation creates opportunities that must be connected with viable local careers. The institutional evidence examined here supports particular concerns about recruitment, real funding levels and the organisation of doctoral support. It also records practical responses through shared supervision, mentoring and revised financial arrangements. The assessment is therefore one of substantial capacity whose continuation depended on deliberate institutional choices about people, facilities and the time required to undertake research well.

Training new researchers brought these choices into focus. A geological research system renews itself when students acquire the ability to move between observations, analytical results and competing explanations, and when institutions provide conditions in which that ability can develop into an independent career. The studies and reports considered in this chapter show several routes towards that outcome, from collaborative field research to reference-material development and the interrogation of digital models. By 2025, sustaining those routes was a central task alongside producing new scientific results. The future value of the accumulated knowledge rested partly on whether a succeeding researcher could recognise its assumptions, test it against fresh evidence and explain why an interpretation should be retained or changed.

Part Five

Geomorphology and the Study of Landscape Evolution

Czech Geomorphology after 1993: Research Traditions, Process-Based Approaches and New Explanatory Models

Czech geomorphology developed after 1993 through the renewal of an established research tradition. Detailed knowledge of landforms and their regional relationships remained essential, while improved dating, instrumental observation and experimental work made explanations of landscape evolution more open to independent testing. By 2025, studies undertaken by Czech researchers connected the history preserved in terrain with the physical processes capable of producing or modifying it. The development was uneven across subjects and institutions, and it cannot be reduced to the adoption of a single new theory. Its clearest expression was a growing ability to ask when a landform developed, which mechanism was responsible and what evidence could distinguish competing explanations.

The inherited tradition gave considerable weight to geomorphological mapping, regional classification and the reconstruction of successive stages of relief development. Jaromír Demek's work remained a point of reference within this approach. The second edition of *Hory a nížiny*, edited by Demek and Peter Mackovčin in 2006, continued the national geographical lexicon of mountains and lowlands. Such compilations preserved the regional vocabulary within which particular observations could be compared. A terrace, escarpment or upland surface acquired scientific meaning through its relationship to a wider landscape. That spatial discipline remained useful as researchers acquired instruments capable of measuring processes and dating deposits with increasing precision.

Professional organisation also showed continuity across the political changes. The Czech Association of Geomorphologists traces its origins to the Geomorphological Commission of the Czech Geographical Society, established in 1988. The grouping became a national partner of the International Association of Geomorphologists in January 1994, and the independent association was officially founded on 25 January 1999. These dates place the creation of the Czech state within an existing scientific history. The 1990s brought a clearer organisational identity and an international framework for a community whose research subjects already extended across university departments and Academy institutes. Institutional independence developed alongside continued participation in the wider geographical sciences.

The combination of regional knowledge and international analytical cooperation was already visible during the first decade. A report published in *Opera Corcontica* in 2002 by Jean-Luc Mercier, Didier Bourlès, Jan Kalvoda, Zbyněk Engel and Régis Braucher described the application of cosmogenic beryllium-10 dating to glacial and periglacial landforms in the Krkonoše Mountains. The method used nuclides produced through exposure to cosmic radiation to constrain the history of rock surfaces. Its application brought a numerical

timescale to features previously interpreted largely through their position and appearance. The importance of this early work lay in the questions it made accessible, including the timing of glacier withdrawal and the survival of cold-environment landforms.

Different parts of the country offered different opportunities for pursuing such questions. The Bohemian Massif preserved long histories of denudation and river incision, while the flysch landscapes of the Outer Western Carpathians exposed the interaction of layered bedrock with widespread slope instability. Sandstone plateaus supplied distinctive weathering and rock-failure problems, and formerly glaciated mountains retained deposits that could be compared across national borders. These contrasts helped sustain a varied discipline. They also encouraged researchers to test whether an explanation developed in one setting remained convincing elsewhere. The national synthesis *Landscapes and Landforms of the Czech Republic*, edited by Tomáš Pánek and Jan Hradecký in 2016, made this diversity accessible within a common regional account.

River terraces provided a particularly clear connection between inherited scholarship and renewed explanation. In 2004, Jaroslav Tyráček, Rob Westaway and David Bridgland reassessed the terraces of the Vltava and Labe system using relationships with glacial deposits and biostratigraphical evidence to correlate the fluvial record with marine oxygen-isotope stages. Comparison extended downstream into Germany. This placed Czech valley histories within a larger Quaternary chronology and allowed terrace development to inform interpretations of regional uplift. The scientific advance depended on retaining the detail of local sedimentary relationships while examining their consistency within an external timescale. A terrace staircase could then be considered as evidence of changing environmental conditions and progressive incision through an evolving landscape.

Work by Břetislav Balatka and Jan Kalvoda in 2008 pursued the relationship between terrace accumulation and uplift in the central Bohemian Massif. Their analysis distinguished seven principal terrace accumulations, with additional subordinate levels, in the Vltava, Berounka, Sázava and Labe valleys. The interpretation linked alternating accumulation and erosion to climatic changes and differential uplift. It illustrates the continued analytical value of field survey, longitudinal profiles and sediment correlation. The height of an abandoned river surface records a history that must be reconstructed through several kinds of evidence. An explanatory model becomes stronger when its proposed sequence of incision agrees with both the deposits and the geometry of the valley system.

Tectonic geomorphology acquired a more direct means of testing the origin of mountain-front relief. Petra Štěpančíková and colleagues reported trenching across the south-eastern Sudetic Marginal Fault in 2010. Digital terrain analysis, field observations and geophysical investigation guided the selection of excavation sites. Exposed sediments and structures were used to distinguish successive phases of movement, including evidence interpreted as prehistoric earthquake displacement. This approach reached beneath a surface whose tectonic expression had been altered by erosion and slope processes. It also qualified the convenient description of the Bohemian Massif as a stable ancient terrain. Long geological stability at a broad scale remained compatible with local Quaternary deformation that required its own chronology and structural explanation.

Digital methods strengthened regional synthesis as well as local investigation. In 2011, Demek, Balatka, Karel Kirchner, Mackovčin, Pánek and Petr Slavík published a quantitative assessment of Czech relief using a geographical information system and a national geomorphological map at a scale of 1:500,000. The polygon data allowed the extent of landform categories and geomorphological diversity to be evaluated across the country. This was a development within the mapping tradition itself. Regional interpretation supplied the categories; computation made their distribution measurable. The analysis also demonstrates why digital precision must be read in relation to map scale and classification. A national dataset can reveal broad spatial patterns while leaving the mechanism responsible for an individual slope or valley to more detailed research.

Airborne laser scanning subsequently changed the visibility of slope deformation in forested terrain. Pánek, Michal Břežný, Veronika Kapustová, Jan Lenart and Vladimír Chalupa published a new inventory of the Czech Flysch Carpathians in 2019. More than 13,600 landslides were mapped, including large failures and deep-seated gravitational slope deformations. The study identified geological controls as particularly important to the distribution of the larger forms. Its implications extended beyond an improved list of hazardous sites. Terrain that appeared relatively undisturbed could contain extensive evidence of earlier mass movement. The resulting landscape history required the recognition of inherited deformation and the separation of visible form from present activity. Greater observational detail altered the population of landforms available for explanation.

Individual failures offered opportunities to investigate how inherited conditions became active. The long-runout rockslide on Girová Mountain during the extreme rainfall of May 2010 was examined by Pánek and a multidisciplinary team in a study published the following year. Their account related rapid failure to structurally predisposed, deeply weathered flysch bedrock weakened by faults. The event brought together conditions developed over a long interval and a short episode of intense rainfall. Distinguishing these timescales is essential in process geomorphology. Rainfall helps explain why movement occurred at a particular moment, while the structure and condition of the rock mass help explain why that slope was susceptible and why failure developed in that form.

The study of deep-seated gravitational slope deformation made the relationship between slow evolution and sudden movement more explicit. In their 2016 review, Pánek and Jan Klimeš examined deformations expressed through features such as doubled ridges and uphill-facing scarps. Dating and monitoring indicated that these systems could undergo prolonged creep as well as episodic displacement. Some large catastrophic failures had developed within slopes already affected by such deformation. This interpretation connected landforms to a continuing mechanical history. It also established a demanding research problem: a surface pattern may indicate deformation without revealing its rate, duration or likelihood of collapse. Chronology and displacement measurements were needed to determine which part of that history the observer was seeing.

By 2025, investigations were combining these approaches within detailed reconstructions of individual mountains. Chalupa, Pánek, Břežný, Francisco Gutiérrez and Alicia Medialdea examined a deep-seated deformation at Travný in the Czech Flysch Carpathians using terrain

mapping, structural measurements, geophysics, trenching and geochronology. The study connected instability with inherited fractures and the arrangement of stronger sandstone above weaker rocks. It identified episodic movement, including a displacement episode around 9,900 years ago that the authors associated with climatic change near the transition to the Holocene. The explanation brought together rock structure, valley development and environmental history. Its relevance lay partly in showing how substantial gravitational deformation could develop in mountains with moderate relief and limited tectonic activity.

Tree rings provided a complementary record at shorter timescales. Karel Šilhán's 2021 review of different landslide types examined how movement could be reconstructed from disturbances in tree growth. Tilting, root damage and burial can leave recognisable signals, but their expression varies with the mechanism of movement and the trees available for sampling. Dendrogeomorphology therefore contributed more than a convenient series of event dates. It required an explicit relationship between biological response and geomorphic disturbance. Šilhán also examined limitations arising from sample selection and signal extraction. These qualifications mattered because an incomplete or insensitive tree population could produce an incomplete movement history. Reconstructing recurrence demanded attention to how the natural archive had formed.

In river research, process explanations increasingly examined the relationship between water discharge, sediment supply and channel form. Tomáš Galia and Václav Škarpich's study of steep Carpathian headwaters, published in 2016, compared coarse bed material with stream power under ordinary and larger flood conditions. Channels containing deposits from earlier debris flows behaved differently from those dominated by fluvial transport. The inherited sediment population affected what later flows could move. This gave a physical explanation for differences that could be obscured by treating all steep channels alike. Channel geometry and present discharge had to be interpreted alongside the history of material supplied from adjoining slopes. Landscape evolution consequently included periods of storage and restricted transfer as well as active transport.

The material moving through a catchment also included wood. Galia, Radek Tichavský, Škarpich and Šilhán investigated a headwater channel after an exceptional hydrogeomorphic event in a paper published in 2018. Their analysis considered the transport and storage of large wood and the role of check dams in retaining it. The case showed how vegetation and constructed barriers could influence the distribution of material during a powerful event. It broadened the physical system under investigation beyond water and mineral sediment. For landscape interpretation, the consequence was practical: the same rainfall could produce different downstream effects depending on what was available for transport and where movement was interrupted.

Human alteration of drainage and land use was already part of the explanatory agenda during the 2000s. Jakub Langhammer and Vít Vilímek's 2006 discussion of landscape change and flood risk examined the relationship between anthropogenic modification, runoff conditions and vulnerability. Such work joined physical investigation to questions concerning settlement and management. It required researchers to distinguish the production of a hazardous event from the conditions determining its consequences. A modified channel or floodplain could

affect the passage of water through a catchment, while the location and character of exposed property influenced damage. This perspective gave applied geomorphology a role in evaluating how inherited engineering decisions interacted with natural processes.

Glacial research meanwhile developed more closely constrained regional chronologies. Engel and collaborators from France and Poland published a beryllium-10 exposure-age chronology for the Krkonoše Mountains in 2014. Moraine boulders on both sides of the range were examined alongside relative-age evidence. The results placed important preserved moraines around 21,000 years ago and identified later glacier fluctuations. Numerical dating allowed local sequences to be compared with other Central European mountains. Its interpretation still depended on geomorphological judgement concerning the surface that had been sampled and the event represented by its exposure. The method improved the questions that could be answered while retaining the need for careful reconstruction of deposition and subsequent disturbance.

Periglacial research also began to formulate quantitative reconstructions from inherited ground structures. Tomáš Uxa, Marek Křížek and Filip Hrbáček introduced PERICLIMv1.0 in 2021 as an inverse model for estimating past air-temperature characteristics from former seasonal thaw depth in permafrost terrain. Applied experimentally at Czech sites, the model used relict cryoturbation structures to constrain past conditions. This made the reasoning between an observed feature and a climatic interpretation explicit. Ground properties and assumptions about temperature seasonality became inputs whose influence could be assessed. Distribution of the code as an R package made the procedure available for inspection and reuse. The model's value rested on its stated physical relationships and evaluation, with uncertainty remaining part of the reconstruction.

Sandstone research produced one of the period's clearest experimental explanations of landform shape. In 2014, Jiří Bruthans and colleagues proposed negative feedback between stress and erosion. Laboratory experiments and numerical modelling showed how removal of loose grains could concentrate load within the remaining material, increasing grain interlocking and resistance to further erosion. Discontinuities helped determine which shapes survived. Pillars, pedestals and arches could therefore emerge through the interaction of mechanical stress with material removal. The explanation was especially significant because it proposed a mechanism that could be examined experimentally. Its application required attention to material properties and structural conditions; it did not establish a universal cause for every sandstone form or eliminate the roles of water and weathering.

Research on smaller sandstone cavities continued to refine the processes involved. Jakub Mareš, Bruthans, Alžběta Studencová and Michal Filippi examined moisture patterns and fluxes in tafoni in a temperate environment in 2024. Their measurements connected water supplied from the rock interior and infiltrating runoff with evaporation and salt accumulation. Greater evaporation from cavity backwalls promoted salt deposition and weathering there, contributing to cavity deepening. Instruments adapted from soil hydrology helped identify where water moved and where evaporation occurred. This offered a process explanation for the changing geometry of a weathering form. It also demonstrated how a familiar feature could

yield new understanding when measurements addressed the internal circulation of water within the rock.

Taken together, these studies reveal a widening range of explanatory models. Some reconstructed histories from dated deposits, others described sediment transfer or mechanical deformation, and experiments identified feedbacks capable of generating particular shapes. They operated at different spatial and temporal scales. A mechanism established for grain detachment could inform the interpretation of a rock surface without, by itself, explaining the evolution of an entire plateau. Equally, a regional terrace correlation could constrain long-term incision while leaving the behaviour of an individual flood unresolved. Productive synthesis required an account of how the scales connected and which observations belonged to each proposed process.

The national research tradition remained visible within this methodological diversity. The 2016 Landscapes and Landforms volume brought regional interpretations together across settings that included sandstone country, volcanic terrain and formerly glaciated mountains. Such synthesis served a different purpose from an individual experiment or monitoring campaign. It placed local findings within geographical relationships that readers could follow in the field and compare between regions. Regional synthesis provided the setting within which a dated sample, measured displacement or tested mechanism could contribute to an intelligible history of relief.

Across 1993–2025, Czech geomorphology thus strengthened the connection between regional interpretation and evidence for the processes producing change. Early international dating projects, the quantitative renewal of national mapping and later investigations combining several methods belonged to an overlapping development. By the end of the period, researchers could examine previously concealed deformation, estimate the timing of landscape events and test mechanisms under controlled conditions. The resulting explanations remained conditional on the quality of the archive and the suitability of the method. This was a productive form of continuity: detailed attention to place endured, while the grounds on which a history of that place could be accepted became more explicit.

Fluvial, Slope and Karst Processes: The Formation and Transformation of Landforms

Between 1993 and 2025, Czech research on fluvial, slope and karst processes provided increasingly detailed explanations of the formation and transformation of landforms. Rivers transported material delivered from adjoining slopes, failures exposed new rock surfaces and redirected drainage, and underground streams enlarged or filled passages in limestone. Investigation of these relationships required attention to both contemporary activity and inherited conditions. The published record shows a growing capacity to connect historical maps and field observations with measurements of sediment, rock strength and water

chemistry. The resulting explanations concerned the behaviour of particular systems, including the circumstances under which a seemingly stable landform could begin to change.

Fluvial research examined how earlier engineering and land-use decisions influenced the operation of rivers during the study period. Jakub Langhammer and Milada Matoušková's investigation of the Blanice basin, published in 2006, combined historical maps, aerial imagery and field mapping to assess modification of the drainage network. The basin had been heavily affected by the August 2002 flood. Their approach located changes within the river network and considered their significance for flood passage and the capacity of floodplains to accommodate water. It helped establish a spatially explicit basis for examining human influence. Straightening or reinforcing a channel altered conditions within a connected system whose behaviour also depended on the character of reaches farther upstream and downstream.

The Morávka River provided a particularly informative example of channel transformation. In 2013, Václav Škarpich, Jan Hradecký and Radek Dušek reconstructed changes in a reach where an anabranching pattern had been replaced by a narrower channel incised into bedrock. Average active-channel width declined from 153 metres in 1836–1852 to 44 metres in 2010. These historical comparisons enabled research conducted after 1993 to identify the longer development behind contemporary erosion. Channel regulation, bank stabilisation and dams were considered alongside changes in land cover and the erodibility of flysch bedrock. The interpretation connected restricted sediment supply with the river's ability to remove material. Exposed claystone layers offered relatively little resistance, allowing erosion to proceed rapidly in susceptible sections.

Research in headwater streams clarified how sediment reached such river systems. Tomáš Galia and Škarpich studied coarse bed material in the Moravskoslezské Beskydy Mountains in 2013, using changes in the largest boulders along a channel to investigate sediment delivery and slope–channel coupling. The coarsest material occurred where interaction with adjoining slopes was especially strong. This made bed sediment an indicator of the processes supplying a channel as well as the flows passing through it. A boulder could persist after the event that delivered it and influence later channel adjustment. Reconstructing formation of the bed therefore required knowledge of nearby slopes and the continuity of sediment transfer along the stream.

The Bečva demonstrated how large floods could partially reverse an engineered channel pattern. A study published by Škarpich, Galia, Stanislav Ruman and Zdeněk Máčka in 2019 compared sediment from 68 gravel bars along a 14-kilometre reach with modelled hydraulic conditions. Some sections retained a regulated single channel, while others had widened and regained multiple channels after floods in 1997 and 2010 damaged regulation structures. The re-naturalised sections offered conditions favouring deposition of gravel bars. Sediment sizes also reflected lateral supplies and interruptions to transport, complicating a simple relationship with local flow hydraulics. The research showed that recovery depended on what a flood could mobilise and where the valley allowed material to accumulate.

The relationship between sediment supply and vegetation became central to assessing the future of remaining multiple channels on the Morávka. In 2020, Škarpich, Tereza Macurová, Galia, Ruman and Hradecký examined bar vegetation, erosion and sediment transport. Vegetation colonisation reinforced formerly open gravel surfaces and contributed to declining channel mobility. At the same time, sediment deficits encouraged incision. The authors proposed measures including vegetation disturbance, artificial floods and sediment supplementation to sustain channel dynamics. These were recommendations arising from the analysis, rather than evidence that a complete restoration programme had already succeeded. Their physical reasoning was consequential: providing additional water alone might increase erosion where a river still lacked enough mobile gravel to maintain its channel pattern.

Attention also extended to modest changes between major events. Galia, Škarpich, Adriana Holušová and Hradecký monitored four bars on the regulated Labe, or Elbe, for two years in work published in 2024. Surface sediment and heterogeneity changed even though flows did not reach the discharge associated with a one-year recurrence interval. Different parts of individual bars showed different trends of coarsening or fining. Such observations qualified the assumption that meaningful geomorphic adjustment could be understood entirely through exceptional floods. The interval between large events also affected the surface available for subsequent erosion, deposition and colonisation. Repeated observations revealed changes that a single survey might conceal within an apparently persistent bar outline.

These fluvial studies strengthened an interpretation of river form based on the balance and distribution of material. Incision, bar formation and channel widening were related outcomes of transport through reaches with different constraints. A sediment source beside one reach could supply another, while a barrier could interrupt that transfer. The historical dimension remained essential because contemporary channels inherited the effects of regulation, earlier floods and sediment storage. The Czech evidence consequently supported assessments made at connected reach and catchment scales, with local measurements interpreted within the history of the river system.

Slope research had an especially strong impetus from the widespread instability associated with the 1997 floods. The Czech Geological Survey dates its systematic programme of slope-deformation mapping to that year. Mapping and documentation provided a continuing basis for identifying unstable terrain and comparing different forms of movement. This mattered scientifically as well as practically. An inventory preserved evidence beyond the immediate aftermath of an event, when scarps and deposits were most conspicuous. It also enabled later investigations to examine inherited deformation surrounding a recent failure. The expansion of recording thus supported a longer view of slope evolution than could be obtained from emergency inspection alone.

Ivo Baroň, Václav Cílek, Oldřich Krejčí, Rostislav Melichar and František Hubatka demonstrated the complexity of flysch-slope development in a 2004 study of three deep-seated failures in the Magura Nappe. The investigated failure surfaces extended approximately 50–110 metres below ground, and the cases differed in movement mechanism and activity. Their development was related to rock structure, lithology, weathering and clay behaviour, with heavy rainfall acting within this preconditioned setting. The reconstructions indicated several

phases of movement. A landslide body therefore preserved a sequence of changes rather than a single episode with a single cause. Understanding its morphology required the investigation of conditions inside the slope, where weak layers and fractures could organise movement on a much larger scale than surface disturbance suggested.

The relationship between geological inheritance and new disturbance became particularly visible at Dobkovičky in the České středohoří Mountains. A landslide on 6 June 2013 damaged a section of the D8 motorway then under construction. Jan Klimeš's mapping study, published in 2018, examined the wider surrounding slopes, using field investigation and terrain data derived from laser scanning. Basaltic rocks overlying sedimentary formations were associated with deep-seated block spreading and a variety of shallower movements. The published account made clear that the area already possessed a substantial history of deformation. Analysis of the recent failure consequently required a regional structural setting, alongside investigation of the immediate site. The new road crossed a landscape whose movement history could not be represented adequately by the outline of the 2013 landslide alone.

Laboratory work supplied a further part of the explanation. Jakub Roháč, Petr Kycl, Jan Boháč and David Mašín examined clay and tuff from the Dobkovičky rupture surface in 2017, determining critical and residual friction angles. Such measurements addressed the material resistance involved in sliding. They also connected geomorphological evidence with engineering geology, where the behaviour of a previously sheared surface may differ from that of less disturbed material. The investigation illustrates the need to relate visible displacement to the properties of the zone in which movement occurs. A map can locate a failure and describe its form; laboratory analysis contributes information needed to evaluate the mechanical interpretation.

Sandstone rockfalls involved a different combination of gradual weakening and rapid change. Filip Hartvich and Czech–Polish collaborators investigated the collapse of a pillar in the Teplické skály rock city during the night of 11–12 November 2021, publishing their results in 2025. The approximately ten-metre pillar fell onto a tourist trail. Field observations, petrography, strength measurements and 3D reconstruction supported an interpretation involving toppling of a chemically altered rock body with a narrow supporting stem. A sudden temperature decrease before the collapse was identified as a likely trigger through frost action. The study separated the long development of weakness from the final loss of stability. It also connected an individual collapse with the progressive widening of corridors within jointed sandstone terrain.

Underground openings could themselves provide evidence of slope movement. Jan Lenart, Martin Kašing, Petr Tábořík, Natalia Piotrowska and Jacek Pawlyta investigated Cyrilka Cave in the flysch Carpathians in 2018. The cave developed within the headscarp area of a deep-seated landslide. Structural analysis, cave survey and electrical resistivity tomography revealed the organisation of fractures and suggested further opening upslope. Radiocarbon evidence from material within a stalactite core provided a minimum age approaching 20,000 years, supporting a Late Pleistocene history. Cyrilka is a crevice-type pseudokarst cave: gravitational displacement created the principal openings. This distinction prevents the shape of an

accessible underground passage from being treated, by itself, as proof of formation through limestone dissolution.

The slope investigations exposed an important relationship between the persistence of landforms and continuing activity. A recognisable landslide can contain both slowly deforming sectors and portions capable of rapid failure. Conversely, an opening produced by displacement may survive long after its initial formation. Evidence for age, mechanism and contemporary movement therefore answers different questions. Their combination makes it possible to reconstruct how slopes change through time and how episodes of removal contribute material to valley floors. It also explains why assigning one date or one triggering event to an entire slope can obscure the sequence preserved within it.

Karst research investigated a further means by which water transformed rock and organised drainage. In limestone, dissolution enlarges pathways through which water moves, while changes in water chemistry can produce calcite deposits within the resulting cavities. Mechanical transport may then fill or reopen passages. Czech investigations after 1993 examined these processes at scales ranging from the chemistry of individual drips to the evolution of regional underground drainage. A cave could preserve evidence of earlier flow while continuing to undergo chemical and physical alteration under quite different present conditions.

Jaroslav Kadlec and colleagues' 2001 reconstruction of the northern Moravian Karst combined cave deposits, valley morphology and geophysical evidence. They examined the relationship between subsurface streams and local base levels, together with alternating phases of fluvial sedimentation and speleothem growth. Their analysis also identified the importance of local interruptions to drainage, including collapse associated with the Macocha Chasm. Such interruptions could promote sediment accumulation without corresponding directly to a regional phase of river-terrace formation. The finding discouraged automatic correlation between deposits underground and terraces outside. Cave filling had its own controls, and the sediment preserved in a passage could represent a later episode within a much older cavity.

Dating work in Šošůvská Cave made this distinction more precise. Kadlec, Petr Pruner, Daniela Venhodová, Helena Hercman and Tomasz Nowicki investigated fluvial and infiltration deposits interspersed with or covered by flowstone in 2002. Magnetic polarity records were considered alongside uranium-series dating of flowstone samples. The combination constrained the sequence of deposition through independent chronological evidence. Its geomorphological value lay in establishing relationships among sediment entry, carbonate deposition and the existence of an open passage. A dated deposit could provide a limit on the history of the cavity containing it, while preserving a more specific record of conditions at the time of accumulation. Interpretation required the position of the sample within the deposit sequence.

Investigation of contemporary dissolution examined where chemically effective water acquired its properties. Jiří Faimon, Monika Ličbinská, Petr Zajíček and Ondra Sracek studied permanent drips in Moravian Karst caves in 2012. From water chemistry they calculated carbon-dioxide pressures associated with the preceding limestone dissolution, obtaining values higher than those generally measured in the relevant shallow soils. These were inferred

chemical conditions, not direct measurements of a hidden gas reservoir. The results nevertheless required researchers to consider processes within the karst profile more carefully. The properties of a drip reaching a cave could reflect reactions and storage above it, extending beyond a simple correspondence with the soil immediately overhead.

Pavel Pracný, Faimon, Ludvík Kabelka and Jiří Hebelka extended the investigation in a study of the Punkva Caves published in 2016. Cave-air carbon dioxide and chemical characteristics of dripwater varied seasonally, while reconstructed conditions associated with initial dissolution were comparatively stable. One anomalous drip showed the influence of calcite precipitation before the water reached the observation point. Geochemical modelling examined changes during degassing and carbonate deposition. The study connected cave decoration with an evolving chemical history along the flow path. Speleothem growth depended on the state in which water arrived and the environment it encountered, making the cave atmosphere an active part of the depositional system.

The importance of cave air was also evident in a 2025 study at Výpustek by Marek Lang, Simona Pospíšilová and Jindřich Štelcl. Monitoring during 2024–2025 related temperature differences and airflow to seasonal condensation on a polished limestone tablet. Condensation occurred under the downward-airflow regime, and the surface preserved evidence of calcite alteration through interaction with condensed water. Visitor-related temperature peaks were observed within the broader natural pattern. This work examined small surface changes rather than the excavation of an entire cave, but it identified a mechanism by which existing walls and deposits could continue to be modified. Contemporary transformation thus included effects of ventilation and moisture exchange within cavities already formed.

At Hranice Abyss, geophysical investigation led to a reconsideration of the origin of a much larger underground system. Radek Klanica and colleagues published a model in 2020 based on gravity, electrical, electromagnetic and seismic data interpreted with regional geology. They inferred a karst system extending to approximately one kilometre in depth; this was a modelled subsurface extent, distinct from directly surveyed passage. The authors argued for an important initial role of surface-derived water descending through the rock, with later hydrothermal processes modifying the system. Their interpretation separated the conditions of original formation from the properties of present water. A warm, chemically distinctive groundwater system could therefore overprint cavities whose principal geometry had developed through an earlier drainage configuration.

The connection between surface conditions and underground water also acquired a longer observational record. Jiří Kamas, Jiří Bruthans, Helena Vysoká and Miroslav Kovařík’s 2015 study compared nitrate in cave drips beneath agricultural and forested land in the Moravian Karst. Observations spanning changes in land use revealed differing transport and residence times through unsaturated limestone. Nitrate served as an indicator of water movement, rather than a direct measurement of cave enlargement. The geomorphological implication concerns the routes and delays through which surface change reaches a karst system. Conditions recorded at a drip can include a substantial history of storage and transmission, complicating attempts to relate underground processes to a single recent event overhead.

Across these research areas, the formation of landforms depended on changes in the pathways available to water and material. Flood damage to channel structures could permit renewed bar formation; slope displacement could open fissures; cave collapse could restrict an underground stream and encourage filling. These connections helped explain why a change at one point sometimes produced a delayed or spatially separate response. They also imposed limits on interpretation. A sediment layer, fracture or chemical measurement recorded a particular part of a connected history. Reconstructing that history required evidence for what happened before the observed feature formed and for the conditions maintaining it afterwards.

The development of Czech research between 1993 and 2025 is especially clear in this movement between observed form and investigated mechanism. Post-flood mapping expanded the evidence for unstable terrain, historical reconstructions identified inherited controls on rivers, and combined dating and monitoring clarified the changing operation of underground systems. By the closing years, studies could connect material properties with individual failures and relate chemical alteration to measured cave microclimates. These advances supported explanations sensitive to local geology and to the sequence in which processes occurred. They gave the study of landscape evolution a firmer basis for understanding both gradual adjustment and the short episodes through which a river, slope or cave could acquire a markedly different form.

Quaternary Landscape Evolution: Glacial, Periglacial and Palaeoenvironmental Research

Between 1993 and 2025, research undertaken by Czech geomorphologists and their collaborators substantially refined the history of landscapes shaped during the Pleistocene and Holocene. Glacial landforms, frost structures and sedimentary sequences became increasingly well dated, while biological remains supplied evidence of the environments in which those features developed. An important outcome was recognition of differences between neighbouring places and between successive phases of a cold period. Mountain glaciers, frozen ground and vegetation responded to conditions operating at different scales. Their histories could be compared, but they required evidence appropriate to each process. The resulting reconstructions connected the formation of relief with the changing environments inherited by present-day landscapes.

The early years of the period retained a strong emphasis on evaluating field evidence within established regional histories. Zbyněk Engel’s 1997 review of Pleistocene glaciation in the Czech part of the Krkonoše Mountains assembled knowledge of glacier distribution and the landforms recording it. Cirques, glacial troughs and deposits were considered against the shape of the mountains before glaciation. That distinction remained consequential as dating improved. A glacier modified valleys that already possessed geological and topographical differences. Reconstructing its extent therefore required attention to the inherited relief,

including the contrasting slopes of the range. Later numerical chronologies developed within this continuing tradition of detailed landscape interpretation.

National synthesis also required a distinction between continental and mountain glaciation. Miloš Růžička's 2004 account examined the advance of northern European ice sheets into northern Bohemia and northern Moravia and Silesia, linking the glacial record with regional drainage histories. Daniel Nývlt, Engel and Jaroslav Tyráček's 2011 synthesis brought together continental and mountain evidence, distinguishing the Middle Pleistocene Elsterian and Saalian advances from the mountain record of the Krkonoše, Šumava and Hrubý Jeseník. These accounts provided an essential geographical framework. The existence of glacial deposits on the country's northern margins did not imply that the whole territory had been covered by ice during the last glacial period. Large areas instead preserved evidence of cold conditions operating beyond glacier margins.

Assigning a numerical age to a preserved feature added a different kind of information to its mapped distribution. Cosmogenic exposure dating estimated how long sampled rock surfaces had been exposed, whereas sediment dating and biological archives constrained other parts of the landscape history. The interpretation depended on the event represented by the sample. A boulder on a moraine could help date glacier activity, but its surface also possessed a history of exposure and possible disturbance. Comparison between sites therefore required consistent analytical assumptions as well as suitable samples. This became particularly clear in the development of chronologies for the mountains along the Czech–German border.

Pavel Mentlík and colleagues established a beryllium-10 chronology for the Bohemian Forest in 2013, drawing on moraine boulders in the Prášilské and Laka lake valleys. New measurements were considered alongside recalculated ages from Kleiner Arbersee on the German side of the range. The work connected the Czech sites with a transboundary sequence and identified glacial phases during the Last Glacial Maximum, followed by later activity around 16,000 and 14,000 years ago. Recalculation of earlier measurements using updated production rates made the chronological comparison more consistent. The contribution lay partly in bringing separate valley histories onto a common basis, enabling their relationship with other Central European mountain ranges to be assessed.

Further work continued to alter that chronology at the end of the book's period. Václav Duffek, Engel, Régis Braucher, Mentlík and the ASTER team examined the south-facing Großer Schwarzbach valley on the German side of the Bavarian–Bohemian Forest in a study published in 2025. Their weighted mean exposure age placed the terminal moraine complex at approximately 25,700 years ago, with an uncertainty of about 1,100 years. They interpreted differences among dated moraines across the range in relation to contrasting solar exposure. The study sharpened the problem of regional synchrony. Moraines in neighbouring valleys could stabilise at different times even within the same broad climatic episode, so one local chronology could not simply be extended across the entire mountain system.

Sediment recovered from formerly glaciated basins supplied evidence unavailable from moraine surfaces alone. Engel, Nývlt, Marek Křížek, Václav Treml, Vlasta Jankovská and Lenka Lisá investigated a sequence from Labský důl in the Krkonoše in 2010. Magnetic properties,

carbon content, pollen and plant macrofossils were used to reconstruct environmental history over approximately 30,000 years. The sequence connected changes in sedimentation with glacier activity and subsequent vegetation development. It demonstrated the value of studying the basin as a changing depositional environment. The deposits recorded conditions during and after local glaciation, including the establishment of woodland, rather than supplying only a single date for the disappearance of ice.

Klára Vočadlová and colleagues extended this integration in their 2015 study of the Černé Lake cirque in the Bohemian Forest. Sediment analysis, pollen and macrofossils were combined with luminescence and radiocarbon dating. The reconstruction identified changes in sedimentation during the transition out of the last glacial period and followed the later development of vegetation. In this record, the Younger Dryas cold episode was associated with low lake levels and cold, dry conditions, without a corresponding glacier readvance. The example matters because it separated regional cooling from the particular response of a local glacier. Temperature influenced the system alongside moisture availability and the topographical conditions governing snow accumulation.

Together, these basin and moraine studies supported a more differentiated account of deglaciation. Glacier retreat changed sediment sources and created or exposed basins in which new records accumulated. Vegetation establishment subsequently altered the catchment supplying those basins. A sedimentary transition could therefore reflect several interacting changes, requiring comparison with dated landforms outside the core. This relationship encouraged cooperation between geomorphologists, sedimentologists and palaeoecologists. It also preserved a useful distinction between the history of the ice itself and the longer environmental succession that followed its retreat. The formation of a modern mountain landscape continued well beyond the final survival of its glaciers.

Periglacial research investigated another component of that inheritance. Frost action could disturb sediment and organise surface material in places where glaciers were absent. Stone-sorted polygons and nets preserved on upland surfaces were particularly useful because their geometry recorded repeated movement within freezing and thawing ground. Their interpretation nevertheless required a chronology: a well-preserved pattern need not be active under the present climate. Research during the later part of the period increasingly addressed this problem by combining exposure ages, detailed surface measurement and evidence from structures preserved below ground. These approaches brought both upland and lowland records into reconstructions of former permafrost.

Engel, Křížek, Braucher, Tomáš Uxa, David Krause and the ASTER team investigated large sorted polygons at four Sudetes sites in work appearing in 2021. Exposure ages were interpreted as indicating development beginning towards the end of marine isotope stage 3, with the principal phase between approximately 30,000 and 20,000 years ago. Marine isotope stages provide a numbered climatic framework derived from marine records, within which terrestrial observations can be compared. The polygon study helped place conspicuous upland forms within a particular glacial interval. It also tied their interpretation to chronological evidence, allowing the survival of ancient frost patterns to be distinguished from the climatic conditions observed at their present location.

Uxa, Křížek, Tereza Dlabáčková and Krause examined the geometry of about 2,000 sorted nets at a Krkonoše site in 2023 using high-resolution airborne terrain data and photographs. The work made it possible to assess a substantial population of features, including variation in dimensions and network organisation. Comparison with ground measurements also exposed limits: remotely derived height was less reliable than horizontal dimensions. This was a useful qualification of the apparent precision of digital terrain analysis. Surface datasets broadened the evidence available for interpreting former ground conditions, while field observations remained necessary to establish what the measured geometry represented and how accurately particular dimensions had been recovered.

Lowland frost wedges supplied a different archive. In 2024, Uxa, Křížek, Krause, Piotr Moska and Julian Murton published luminescence ages from seven relict wedges at four north-central Bohemian sites. Their results indicated two main phases of development, centred approximately on 23,600 and 16,100 years ago. The interpretation associated these phases with cold, dry conditions and at least discontinuous permafrost. Dating the sediment within frost structures placed former ground cracking within a chronology of environmental change. It also addressed a geographical imbalance in the evidence: low-elevation terrain between the northern and Alpine ice masses had experienced substantial freezing, although its chronology had remained less securely constrained than that of better-studied European regions.

Evidence from underground provided an additional view of former frozen ground. Karel Žák and a Czech–German team examined coarsely crystalline cryogenic cave carbonate in 2012 as an archive of past permafrost. This carbonate precipitates when mineralised water freezes slowly in cave pools. Stable isotopes, uranium-series ages and depth below the surface helped relate the deposits to former freezing conditions. The authors also considered their formation during episodes of permafrost thawing, when water could enter cavities that remained cold enough to freeze it. The archive consequently recorded changes within the frozen-ground system. Interpretation required suitable cave conditions, including restricted ventilation, before depth could be used to constrain the former extent of permafrost.

By 2025, numerical reconstruction could examine a longer sequence than that preserved by individual frost structures. Uxa and Jan Šafanda simulated permafrost history at the Litoměřice borehole, comparing alternative temperature histories with the measured temperature profile at depth. Their preferred reconstructions indicated major permafrost phases in marine isotope stages 4 and 2, with modelled maximum thicknesses of roughly 80 and 110 metres respectively. These estimates concerned the investigated setting and remained outputs of a model tested against present subsurface temperatures. They were not direct measurements of ancient frozen ground across Czechia. The study nevertheless connected scattered geomorphological evidence with an explicit reconstruction of growth and degradation over the last glacial cycle.

Loess research extended the geographical and temporal coverage of palaeoenvironmental reconstruction. Windblown sediment and the soils formed during intervals of reduced accumulation preserved a sequence of changing surface conditions. At Dolní Věstonice in southern Moravia, Markus Fuchs and collaborators, including Jiří Svoboda and Lisá, published a new luminescence chronology in 2013. Ages derived from several quartz grain-size fractions

were compared with stratigraphical observations and magnetic properties. The resulting framework distinguished successive phases of dust deposition and soil formation, including an early-glacial soil complex spanning approximately 110,000–70,000 years ago. The sequence placed Czech evidence within a much longer climatic history than the terminal stages of the last glaciation alone.

Pierre Antoine and colleagues' accompanying 2013 investigation examined the Dolní Věstonice succession through detailed sedimentology, palaeopedology, magnetic measurements and organic-carbon isotopes. Variations in grain size identified changes in dust deposition, while soil horizons recorded contrasting intervals of surface development. The authors compared this terrestrial sequence with Greenland climatic records. Such correlation provided a way to investigate the response of a Central European landscape to wider atmospheric change. Its persuasiveness depended on the local stratigraphy and independent age constraints. The loess profile was a material record of deposition and alteration whose correspondence with distant archives had to be established through those relationships.

Palaeobotanical work broadened the environmental information recoverable from sediment. Jankovská and Jiří Komárek's 2000 study examined the indicative value of *Pediastrum* and other coccal green algae. Resistant algal remains could survive the preparation of samples for pollen analysis, providing evidence about the former water body alongside the pollen derived from surrounding vegetation. Their ecological interpretation helped reconstruct nutrient conditions and other properties of aquatic environments. The contribution strengthened an existing analytical tradition by drawing attention to material that could otherwise be overlooked. For landscape history, it became possible to distinguish changes within a lake from changes in the terrestrial catchment recorded in the same sediment sample.

The value of earlier fieldwork was clear in Jankovská and Petr Pokorný's 2013 reassessment of the former Komořanské jezero lake in north-western Bohemia. Sedimentary sequences collected during palaeobotanical and archaeological salvage work from the 1970s to the 1990s were considered together through pollen and algal evidence. The reconstruction followed changes in the lake's nutrient status and the vegetation around it through the Late Glacial and Holocene. The authors also discussed difficulties caused by differences in local conditions and transport of pollen, including through flowing water. Reinterpretation depended on understanding how the archive had formed. Earlier samples could answer new questions when examined together, while the origin of their biological content limited the geographical precision of the conclusions.

The character of glacial vegetation itself became an important subject of revision. In 2008, Jankovská and Pokorný presented pollen and macrofossil evidence from the Western Carpathians supporting the persistence of coniferous forest in favourable valleys during the last full-glacial period. Their interpretation also recognised surrounding mosaics of open vegetation. This added a spatially differentiated biological history to the evidence for cold ground and active sediment movement. Shelter and local moisture conditions could support vegetation unlike that of more exposed terrain. The result required reconstructions to accommodate variation within a region, rather than assigning a single vegetation formation to every landscape experiencing the same broad glacial climate.

Comparative fieldwork supplied another means of testing such interpretations. Petr Kuneš, Barbora Pelánková, Milan Chytrý, Jankovská, Pokorný and Libor Petr compared Czech and Slovak fossil pollen assemblages with modern samples from southern Siberia in 2008. Samples from different forest, steppe and tundra settings provided an empirical basis for assessing possible analogues. The comparison supported a pattern of wooded valleys and more open landscapes, with differences between the Western Carpathians and the Bohemian Massif. This approach linked regional archives with observations beyond Central Europe. Its value depended on comparison of actual pollen assemblages and vegetation, with modern sites serving as interpretative analogues for selected properties of former environments.

New fossil evidence gave the discussion a further geological dimension in 2024. Jan Hošek and colleagues investigated silica-rich deposits associated with ancient springs in southern Moravia, reporting evidence for the local persistence of temperate trees during the Last Glacial Maximum. Plant remains and geological observations supported an interpretation in which warm groundwater maintained favourable conditions within an otherwise cold region. The study connected the morphology and sedimentary record of former spring sites with the survival of organisms including oak, linden and ash. It demonstrated a specific mechanism for a local refuge. The findings did not imply widespread temperate woodland across glacial Czechia; their significance concerned the capacity of particular geological settings to sustain exceptional environmental conditions.

Holocene reconstruction also became more explicit about separating climatic influence from human activity. Vachel A. Kraklow and colleagues investigated Šumava peat sequences in 2024, combining reconstructed water-table changes with pollen, plant remains, geochemical evidence and archaeological information. Their analysis favoured climate as the principal long-term influence on forest succession and fire, while identifying human use of mountain environments from roughly 4,600 years ago and clearer direct modification during the last millennium. These conclusions depended on the studied sites and analytical framework. The research showed how a modern forest landscape could contain interacting histories of hydrology, vegetation and human use. Interpretation required evidence able to distinguish those influences through time, rather than inferring a single cause from a changing pollen sequence.

The development of these research fields drew together expertise distributed across Czech universities, Academy institutes and scientific services. The publications connected geomorphological survey with geophysics, botanical identification and sediment analysis, frequently through international laboratory and field collaboration. The Bohemian Forest chronologies required comparison across the German border, while pollen research used Slovak records and Siberian analogues. Such geographical extension was integral to testing explanations of Czech landscapes. The relevant processes and comparison sites seldom followed state boundaries, and a local sequence became more informative when its chronology and environmental interpretation could be assessed against evidence from elsewhere.

Chronological precision remained inseparable from the meaning of the material dated. Exposure ages concerned rock surfaces, luminescence constrained the burial history of

sediment, and radiocarbon measurements dated suitable organic remains. These observations could support a common reconstruction while referring to different events within it. A useful landscape history explained their relationships, including the lag between physical change and the biological response recorded in a basin. The increasingly detailed studies of the period therefore raised standards of interpretation alongside increasing the volume of data. Agreement among independent archives was persuasive when the depositional or geomorphological context explained why the records should correspond.

By 2025, Czech Quaternary research had developed a considerably more differentiated account of landscape evolution. Regional reviews and field classifications had been supplemented by chronologies capable of testing the timing of glacier activity, measurements of inherited frost patterns and reconstructions of environmental conditions extending across several archives. The clearest shared outcome was recognition of place-specific responses within wider climatic change. A cold interval could produce glacier growth in one valley, severe ground freezing elsewhere and continued biological survival at a favourable spring. Reconstructing those relationships made the present landscape intelligible as the outcome of successive processes operating at different rates, with some traces preserved and others altered or removed.

Geomorphological Hazards, Landscape Monitoring and the Protection of Geomorphological Heritage

Between 1993 and 2025, Czech geomorphology developed closer connections between the investigation of dangerous processes and the care of valued landscapes. Landslides and rockfalls required decisions about roads, buildings and public access, while river restoration and geoconservation called for a better understanding of how landforms changed. These practical demands encouraged repeated measurement, more accessible inventories and explicit assessment of consequences. They also exposed a difficulty that runs through the history of the subject. A process that threatens a settlement may help create the very landscape protected in a neighbouring reserve. Research therefore had to establish where intervention was necessary and what should be allowed to continue under observation.

The geographical distribution of the problems gave this work a strongly regional character. In the Outer Western Carpathians, weak flysch strata and inherited landslide terrain favoured recurrent slope movement. In the České středohoří Mountains, instability affected slopes where volcanic rocks and weaker underlying formations met, including the corridor of the D8 motorway. The sandstone districts of northern Bohemia presented a different setting, with jointed cliffs and detached blocks above roads, villages and tourist paths. These were contrasting research environments. A regional inventory, a model of rockfall trajectories and a gauge installed across a fracture answered different questions, although all could contribute to the management of the same territory.

The large landslide episode associated with the July 1997 floods gave renewed urgency to systematic documentation. The Czech Geological Survey dates its systematic mapping of slope deformations to 1997, a development that continued an older national tradition of engineering-geological investigation. Field recognition remained fundamental, but its results increasingly entered digital text and map databases. Recording a landslide meant identifying its extent and condition in a form that could be consulted beyond the original survey team. This extended the usefulness of geomorphological knowledge to spatial planning and public administration, while preserving the need for expert interpretation of the mapped terrain.

Subsequent events demonstrated why an inventory needed to retain the history of a slope. Tomáš Pánek, Rudolf Brázdil, Jan Klimeš and their collaborators documented more than 150 landslides associated with the prolonged heavy rainfall of May 2010 in eastern Czechia. Most occurred within older landslide terrain, indicating repeated movement in places already predisposed to failure. Many were relatively small, whereas the Girová Mountain rockslide involved an estimated two to three million cubic metres of material. The resulting account connected precipitation and antecedent saturation with the properties of the affected slopes. It also showed that the aftermath of an event could include partially developed failures whose subsequent behaviour remained relevant. The landscape inherited from earlier movement was an active element in contemporary hazard assessment.

By the closing years of the period, national documentation had become a substantial research and public-service resource. The Geological Survey's annual report for 2024 recorded 25,779 slope-deformation objects at the end of that year. It described an inventory compiled at a mapping precision of 1:10,000, drawing together records produced by different organisations since 1962, with responsibility fully transferred to the Survey in January 2011. Activity classes were attached to the condition observed during mapping, and field revision remained part of the work. These details matter when using the figures historically. The accumulation of records reflects survey coverage, revision and the integration of older information as well as newly identified movements. It cannot by itself establish a national increase in landslide frequency.

Historical research supplied another temporal perspective. In 2021, Michal Bíl, Pavel Raška, Lukáš Dolák and Jan Kubeček presented CHILDA, the Czech Historical Landslide Database. The published dataset contained 699 records of landslides, rockfalls and other movements, extending from 1132 to 1989. Its purpose was to recover events known through documentary evidence and to unite previously fragmented regional datasets. Chronicles, administrative documents and images brought past damage and community responses into the analysis. Their survival and detail varied between places, so a documentary record required critical assessment before it could support a chronology. This work broadened modern geomorphology by treating the historical record as evidence of both physical events and their social setting.

The relationship between scientific knowledge and effective prevention became an explicit research subject. A 2017 study led by Jan Klimeš examined the difficulties of landslide management in a country often regarded as having relatively low risk. The authors compared inventories assembled from geological records, web sources and traffic information, and investigated government expenditure on mitigation. Geological documentation was the most

complete, but the other sources could supply missing events. The uneven distribution of costs could not be explained by the occurrence of landslides alone. Their analysis directed attention towards public awareness, institutional decisions and the exposure of infrastructure. A technically competent research community still needed durable ways of communicating information to those responsible for acting upon it.

The D8 motorway provided a particularly concrete setting for the development of monitoring methods. A major landslide crossed the motorway under construction near Dobkovičky in June 2013. Kateřina Fárová, Jan Jelének, Veronika Kopačková-Strnadová and Petr Kycl subsequently investigated deformation along the corridor using Sentinel-1 radar observations, publishing their comparison in 2019. They evaluated conventional differential radar interferometry and persistent scatterer interferometry, which uses repeated observations of radar targets to estimate displacement through time. Geodetic measurements, inclinometers and laser scanning supplied independent checks. Both satellite approaches identified areas of displacement, while the persistent scatterer results agreed particularly well with the measured magnitudes. The study made the advantages of freely available Copernicus data tangible within Czech applied geomorphology. Its interpretation concerned deformation observed during the monitoring period; the satellite record was not a direct observation of the earlier landslide's initiation.

Quantitative rockfall research likewise required comparisons between alternative representations of a process. In 2013, Jan Blahůt, Klimeš and Zuzana Vařilová assessed hazards and risks to buildings in selected municipalities of the České Švýcarsko National Park. They compared two modelling approaches, CONEFALL and RockFall Analyst. Their predictions were similar on relatively steep, short, convex slopes but diverged on longer, less steep and concave slopes. Differences in predicted runout consequently affected the calculated risk to exposed buildings. The study demonstrated why a hazard map depended on model assumptions and terrain configuration. It also made a useful distinction between the area that falling rock might reach and the consequences for particular buildings within it.

Operational monitoring established a continuing link between such research and the daily management of protected landscapes. The geological rock-management team created within the České Švýcarsko National Park in 2002 combined inspection of unstable objects with measurements and limited stabilisation work. Jakub Šafránek's 2016 account described manual and automatic monitoring, with additional safety monitoring during remedial operations. Repeated measurements distinguished seasonal opening and closing of fractures from progressive movement. Decisions could differ between apparently unstable blocks according to what lay below them. An observed block whose trajectory avoided infrastructure could remain subject to natural development, whereas a block directly threatening a tourist path could require removal. The purpose of observation was to support a proportionate decision in a particular place.

Pravčická brána brought the relationship between hazard investigation and heritage protection into unusually close focus. Systematic displacement monitoring began there in 1993. In their 2014 study, Vařilová, Jiří Zvelebil, František Hubatka, Vojtěch Beneš and Josef Frolka combined non-destructive investigation with observations of the arch's natural dynamics. They identified

the arrangement of blocks, secondary fractures and zones of weakened sandstone, while geophysical methods helped interpret the internal structure and water regime. Monitoring distinguished slow irreversible displacement from reversible movements associated with temperature changes over days and years. The resulting structural model respected the site's protected character. The arch was investigated as a rock body undergoing measurable change, giving conservation an empirical basis that a visual impression of permanence could never supply.

The documentation of sandstone failures also extended beyond instrumented monuments. The Institute of Geology of the Czech Academy of Sciences established a database of recent and older rockfall phenomena under the Geohazards programme of Strategy AV21. Its institutional description records work in Kokořínsko–Máchův kraj in 2016 and Bohemian Paradise in 2017. Entries combined descriptions with photographs taken at different times, and contributions could come from specialists or members of the public. Such records made otherwise scattered observations available for comparison. Their scientific value depended on the quality of location, timing and photographic evidence, but the initiative widened participation in observing landscape change and improved the prospects of recognising events outside the principal monitored sites.

River research introduced another form of repeated landscape observation. In 2017, Jakub Langhammer, Jana Bernsteinová and Jakub Miřijovský examined how drone photogrammetry and an automated water-level network could be combined in a flood model for Javoří Brook in the Šumava Mountains. 3D reconstruction supplied detailed channel topography, while instrumental records supported calibration. The study tested the influence of alternative ways of dividing the modelled channel into computational units. It also identified limitations in reconstructing the submerged bed from aerial imagery, for which geodetic measurements provided supplementary information. This was a practical development in the relationship between geomorphology and hydrology: channel form could be measured in sufficient detail to examine how water moved through a specific reach during flooding.

Repeated surveys also made environmental interventions open to scrutiny after construction. Langhammer, Theodora Lendzioch and Jakub Šolc reported six years of drone monitoring at three restored streams in Prague in 2023. Their analysis combined reconstructed channel and riparian geometry with qualitative hydromorphological assessment. It identified discrepancies between planned and realised channel forms and problems involving water use, eutrophication, shading and connectivity with the floodplain. The importance of this work lay in observing how a completed project actually functioned through successive seasons. A channel could resemble a desired pattern while remaining constrained by its surroundings or water supply. Monitoring thus became a means of evaluating restoration performance and identifying the local conditions that limited it.

The 2022 wildfire in České Švýcarsko changed the immediate demands placed on landscape monitoring. The park administration's September account described inspections of fire-damaged rocks, the controlled removal of hazardous blocks and camera-equipped drones used to examine the difficult terrain of the Kamenice gorges. The Czech Geological Survey worked with park staff along the approach towards Pravčická brána. Damage to protective

barriers above Hřensko added an engineering problem to the assessment of slopes and access routes. These activities illustrate how one disturbance could alter both the condition of a landscape and the effectiveness of existing protective measures. They also required specialists to reassess particular places before access could be restored, rather than treating the end of the fire as the end of the emergency.

Across these examples, the main methodological gain came from relating observations made at different scales. Satellite radar placed movement within an infrastructure corridor, local instruments followed individual fractures, and drone surveys reconstructed channels or inaccessible slopes. Field examination supplied the geological and geomorphological context needed to interpret each record. A denser time series was valuable when it revealed a meaningful change in behaviour, and a detailed surface model was valuable when it resolved a feature relevant to the process. The Czech studies increasingly tested these relationships through comparison with independent measurements, making the quality of interpretation a central part of technical progress.

Conservation research developed alongside this concern with measurement. Václav Cílek's discussion of geodiversity in *Vesmír* in 2000 brought the importance of substrate and landform variation to a wider Czech readership. His examples from the Bohemian Karst connected differences in bedrock and relief with habitats, while observations in excavated trenches revealed the loss or burial of small landscape features. The argument extended concern beyond conspicuous monuments to ordinary scarps, valley floors and other elements that supported environmental diversity. It gave a clear intellectual reason for documenting landforms before they disappeared under apparently routine alteration. The object of conservation could therefore include a modest feature whose significance became apparent only through careful field observation.

The institutional setting retained substantial continuity with general nature protection. As Lucie Kubalíková explained in her 2016 synthesis, Czech geoconservation had usually developed within that broader framework, with the Act of 1992 providing the principal legislative background to the period after independence. Protected areas formed one part of this system, alongside geological-site inventories, documentation of karst features and national geoparks. This history helps explain why a landform might already possess territorial protection without its scientific interest receiving much explicit interpretation. The research task included identifying what a site recorded about Earth history and how management could retain that evidence within a landscape also valued for habitats or recreation.

The concept of the geomorphosite offered a more explicit language for this work. A geomorphosite is a landform, or an assemblage of landforms, recognised for the value attached to its scientific and other qualities. Kubalíková's 2013 methodological discussion distinguished assessment of scientific significance from additional cultural and aesthetic values, tourism potential and threats. The distinction allowed the reasons for a site's importance to be examined separately from the convenience of visiting it. In the same year, Kubalíková and Karel Kirchner discussed Czech geoconservation and geomorphosite assessment through a study of Podyjí National Park in the French *Collection EDYTEM*. This

placed a Czech protected landscape within a wider European discussion of how to identify, evaluate and manage sites for education and carefully considered public use.

Geomorphological heritage was also being recognised in landscapes shaped by extraction and urban development. In 2017, Kubalíková, Kirchner and Aleš Bajer examined secondary geodiversity in Brno, including old quarries and underground spaces. Their assessment considered the educational and geotourism potential of landforms produced or exposed through human activity, some of which already served as excursion sites. This widened the practical geography of conservation. Scientific interest could be found within a city, where access and interpretation involved different possibilities from those of a national park. An abandoned quarry could reveal geological structure and record the history of resource use, bringing natural and cultural evidence into the same locality.

The geopark movement gave a territorial setting to the interpretation of such relationships. Bohemian Paradise received UNESCO Global Geopark designation in 2015. Its sandstone rock towns and volcanic features could be understood together with mineral working and the stone-cutting traditions of Turnov. This provided an example of Earth-science interpretation extending across a lived landscape with settlements and established visitor routes. For geomorphology, the opportunity was to explain how particular landforms belonged to a wider history and to make that understanding available outside specialist publications. The scientific value of the territory required accurate interpretation, while the popularity of individual places made their continuing observation and management consequential.

By the 2020s, assessment increasingly asked what might damage a site after its value had been recognised. Kubalíková and Marie Balková's 2023 study of the Hády quarries on the outskirts of Brno combined evaluation of individual sites with a risk-assessment matrix for the wider area. The first approach addressed the vulnerability of particular features, while the second considered threats and conflicts arising from their surroundings. This joined site-based conservation with landscape planning. A formally protected exposure could still be affected by activities nearby, and proposed management needed to account for competing uses. The study treated the identification of threats as part of geoconservation itself, giving a more explicit basis for choosing and explaining measures.

Kubalíková's 2024 research on abandoned sand, clay and loess pits in South Moravia developed this approach for dynamic geomorphosites. Erosion, transport and deposition within the pits formed part of their interest, alongside the geological evidence visible in their walls. The study identified the services these places supplied and combined assessment of degradation with a risk matrix to consider their future use. This introduced a subtle management problem. Some change sustained the processes that made a site informative, while other change could remove a significant exposure or conflict with access. Conservation therefore required an account of which features and processes carried value, followed by measures suited to that particular combination.

The regional coverage of heritage research also continued to broaden. In 2025, Kubalíková, Kirchner and the Polish geomorphologist Piotr Migoń examined sandstone crags in the Chřiby ridge of the Moravian Carpathians. They noted the imbalance between the detailed attention

given to Bohemian Cretaceous sandstone areas and the more limited investigation of Moravian flysch crags. Their study combined identification of heritage values with semi-quantitative assessment of threats and degradation risk. Its contribution was both geographical and methodological. It brought less studied landforms into the discussion and made the possibility of deterioration part of their evaluation from the outset, rather than a question postponed until visible damage demanded attention.

Taken together, these developments gave hazard research and heritage protection several shared requirements without making their objectives identical. Both needed reliable inventories, repeated observation and an explanation of why a particular change mattered. Hazard assessment considered consequences for people and infrastructure; heritage assessment considered the retention of scientific evidence and other recognised values. At Pravčická brána, on a monitored tourist path or in an abandoned pit, these concerns could meet directly. Decisions then depended on the local relation between the process, the feature being conserved and the people exposed to it. The most informative Czech examples made those relationships explicit.

By 2025, the field had accumulated a substantial capacity to document unstable terrain, test monitoring methods and evaluate the significance and vulnerability of landforms. The remaining difficulties were visible within that achievement. An inventory needed revision, a monitoring record needed sustained interpretation, and an assessment needed to reach the institutions managing a road or protected site. The history from 1993 onwards therefore concerns the maintenance of scientific relationships as much as the adoption of new instruments. Where field knowledge, repeated measurements and management remained connected, geomorphology could explain an evolving landscape and provide a defensible basis for living with its changes.

Part Six

Climatology, Meteorology and Aerology

Atmospheric Research after 1993: Institutional Development, Observation Networks and Scientific Priorities

Atmospheric research in the Czech Republic developed after 1993 through the renewal of an established scientific system. The new state inherited meteorological services, university teaching and observatories whose records extended well beyond its own lifetime. Its subsequent achievements depended on maintaining those records while changing the instruments, computing facilities and collaborative arrangements through which they were interpreted. By 2025, atmospheric science encompassed operational forecasting, climate reconstruction and research on atmospheric composition, with stronger connections to environmental management and European research infrastructures. Scientific priorities changed alongside the means of observing and interpreting the atmosphere.

The Czech Hydrometeorological Institute, generally known by its Czech abbreviation ČHMÚ or the English CHMI, remained the principal national organisation connecting weather observation with public forecasting and climatological assessment. Its combination of meteorology, hydrology and air-quality responsibilities had developed before independence. The regional organisation was likewise inherited, with branches in Prague, České Budějovice, Plzeň, Ústí nad Labem, Hradec Králové, Brno and Ostrava. Regional offices linked station inspections and the treatment of records with knowledge of local conditions. Establishment of the Central Forecasting Office in 1999 strengthened the organisation of operational work within this continuing national and regional structure.

Basic atmospheric research retained a distinct institutional home in the Institute of Atmospheric Physics of the Czech Academy of Sciences. Founded in 1964, the institute underwent a consequential expansion in 1994, when the ionospheric department of the Institute of Geophysics joined it. Research consequently extended across a greater vertical range, connecting work on the lower atmosphere with studies of the ionosphere and near-Earth space. Conversion to a public research institution on 1 January 2007 subsequently changed its legal framework. Its responsibilities and administrative form thus continued to evolve after independence.

University research provided another source of continuity and renewal. At Charles University, the Faculty of Mathematics and Physics sustained an approach grounded in atmospheric dynamics, thermodynamics and mathematical modelling. Work in this setting linked weather prediction with the study of climate, turbulence, atmospheric chemistry and processes in the middle atmosphere. Its importance lay partly in the education of researchers able to move between theoretical questions and the interpretation of observations. Collaboration with the hydrometeorological service and Academy institutes helped connect teaching with research

problems. The atmosphere could thus be investigated as a physical system while students encountered the practical demands of measurement and forecasting.

Geographical and agricultural traditions supplied complementary perspectives, particularly in Brno. Historical climatology at Masaryk University, associated with Rudolf Brázdil and Petr Dobrovolný, developed an extensive programme of documentary research and the interpretation of early observations. The series *History of Weather and Climate in the Czech Lands* began in 1995 and continued to connect climatic evidence with the history of society. Researchers working across CzechGlobe and Mendel University, including Miroslav Trnka and colleagues in bioclimatology, strengthened the connection between atmospheric conditions and agricultural water availability. These approaches broadened the questions addressed by Czech climatology and brought archives, vegetation and cultivated land into its evidential base.

The growth of CzechGlobe marked a substantial change in the infrastructure available for research on global environmental change. The centre was developed through the Operational Programme Research and Development for Innovation during 2010–2014. A subsequent national sustainability project, implemented in 2015–2019, supported its research and continuing infrastructural development. Climate analysis was placed alongside experiments and observations concerned with ecosystems and the effects of environmental change on society. European investment therefore enlarged the material basis of atmospheric research while encouraging cooperation across disciplinary boundaries. Continued support sustained research and observations after the initial equipment projects ended.

The modernisation of surface observations began early in the period. A detailed account of the CHMI station network published by Pavel Lipina, Miroslav Řepka and Veronika Šustková records the introduction of automation for individual variables at professional stations from 1994. The first major wave of automation among volunteer stations followed during 1996–2003. This was a gradual transition involving different station categories and regional branches. Automatic recording increased the frequency and speed of data collection, although observers continued to contribute measurements and descriptions of weather phenomena. The resulting system combined electronic transmission with the local attention on which station records had long depended.

Automation also brought questions of comparability into sharper focus. A change in instruments, exposure or station location can introduce a discontinuity that resembles a climatic change. Consequently, the scientific value of a larger digital archive depended on quality control, station metadata and the treatment of artificial differences within time series. The 2011 study by Petr Štěpánek, Pavel Zahradníček and Radan Huth examined interpolation methods for checking daily observations, filling gaps and constructing comparable series across a Central European border region. Its connection with the international CECILIA project illustrates how the preparation of national observations became part of a wider methodological effort. Reliable regional climate analysis required agreement about how records were processed.

The *Climate Atlas of Czechia*, published in 2007 through cooperation between CHMI and Palacký University in Olomouc, provided a conspicuous expression of the relationship between observation and geographical synthesis. Radim Tolasz, Taťána Míková, Anna Valeriánová and Vít Voženílek formed its principal production team. The atlas brought climatological knowledge into a cartographic publication accessible beyond individual station records and specialist datasets. Its institutional significance lay in joining the expertise of a national scientific service with university cartography and geoinformatics. The publication preserved a regional synthesis alongside expanding digital and numerical approaches.

Aerology remained an active component of the Czech system. In meteorological usage, it concerns observation and investigation of the free atmosphere, particularly the vertical distribution of temperature, pressure, humidity and wind. At Prague-Libuš, balloon-borne radiosondes provided measurements above the surface network and formed part of international meteorological exchange. These observations made it possible to examine atmospheric stability and wind structure directly, rather than infer them solely from conditions at ground level. Their use in forecasting and research also connected routine operational work with the study of atmospheric processes. Aerological expertise was therefore embedded within the observing service and related research groups, rather than confined to a separately named academic discipline.

The military hydrometeorological service contributed another institutional strand to upper-air observation. Its historical account records the transfer of the radiosonde station from Sokolnice to Prostějov in 2003. Civil and military organisations consequently remained distinct participants in the national observing system. Their relationship also changed in radar meteorology: the last military radar stations at Chrudim and Bechyně ceased operation in August 2000 in connection with the introduction of the CHMI radar in the Brdy hills. This example demonstrates that institutional development could involve concentrating a specialised observing function while retaining cooperation between services.

Ozone observations gave aerological and climatological work a further dimension. The Solar and Ozone Observatory at Hradec Králové maintained a total-ozone record beginning in 1961; Brewer spectrophotometer measurements were added in 1994 alongside the existing Dobson observations. The resulting overlap enabled researchers to investigate instrumental differences as well as atmospheric variation. In 2011, Karel Vaníček, Martin Staněk, Ladislav Metelka and Pavla Skřivánková described the construction of a combined series designed to reduce instrument-dependent effects over 1961–2010. The study shows why maintaining an observatory involves scientific interpretation as well as equipment renewal. A changing measurement system must be understood before its record can support conclusions about environmental change.

Specialised observatories operated by the Institute of Atmospheric Physics complemented the national station network. Milešovka preserved mountain observations originating in 1905, while Kopisty and Dlouhá Louka supported other aspects of the institute’s observational programme. Their role extended beyond supplying another point on a map. Long records and particular exposures made such locations useful for examining atmospheric conditions that differed from those at lowland stations, while specialised instruments could address research

questions outside routine monitoring. The continued operation of established observatories consequently supplied a link between historical climatology and experimental atmospheric physics. Modernisation acquired much of its value from the older measurements with which new observations could be compared.

Radar meteorology underwent a particularly visible renewal during the 1990s and again in 2015. Digitisation of earlier equipment was followed by the development of the two elevated sites at Skalky and on the summit of Praha in the Brdy hills during the second half of the 1990s and around the turn of the century. Together they formed the national CZRAD network. Replacement of both radars in 2015 introduced dual-polarisation Doppler systems. As Petr Novák and Hana Kyznarová explained in their subsequent technical account, the additional measurements improved the possibilities for identifying radar targets, filtering unwanted echoes and correcting attenuation. These changes supported more informative observation of precipitation and severe convective weather.

The scientific importance of radar lay in observing the development of weather systems between individual surface stations. Its rapid volume scans supported precipitation estimation and very short-range forecasting, including the extrapolation of moving precipitation areas. Those products required algorithms and verification as well as functioning hardware. International cooperation through EUMETNET programmes also informed the renewal of the Czech network and the use of neighbouring countries' measurements. Radar development thus illustrates a recurring feature of the period: national investment and international methodological exchange worked together.

Satellite meteorology supplied a broader spatial setting for these observations. The Czech Republic became a member of EUMETSAT in 2010, strengthening its institutional participation in the European system for operational meteorological satellites. Satellite information complemented ground observations by describing atmospheric and cloud structures over areas much larger than the national territory. Cooperation with the European Centre for Medium-Range Weather Forecasts followed a different administrative arrangement, under which the Czech Republic participated as a Co-operating State. These relationships connected Czech forecasting and research to observational and modelling systems whose geographical reach necessarily exceeded national boundaries.

Numerical weather prediction became a field of sustained Czech participation in international development. Within the ALADIN and RC LACE collaborations, Czech scientists helped develop a shared forecasting system. An agreement with Météo-France formalised cooperation in 1994. In 1998, ALADIN/LACE operations moved from Toulouse to Prague, where CHMI hosted the regional centre until the end of 2002; Radmila Brožková led this centralised phase. From January 2003, cooperation adopted a decentralised organisation, with national centres maintaining their operational systems while coordinating research. The Prague period brought visiting scientists and model development into close contact with a national service, making scientific exchange part of everyday operational work.

The subsequent refinement of forecasting models placed greater demands on both computation and observation. CHMI's account of changes introduced in 2019 describes a

reduction in the ALADIN horizontal grid spacing from approximately 4.7 to 2.3 kilometres. Finer representation made local terrain and atmospheric structures more accessible to numerical treatment, while also requiring careful assessment of model behaviour. A smaller grid spacing could not by itself remove uncertainty in cloud processes or the initial atmospheric state. The development of numerical prediction consequently encouraged continuing work on physical parametrisation, the incorporation of observations and forecast verification. Computing facilities mattered because they enabled these research choices to be tested under operational time constraints.

Research on atmospheric composition expanded through a different kind of network. Košetice Observatory, established before 1993, continued observations of background air pollution and meteorological conditions within international programmes. Its participation in EMEP and Global Atmosphere Watch linked national measurements to the investigation of transport and change across larger regions. Automatic meteorological measurement with human attendance was established there by 2001. Subsequent participation in European aerosol projects enlarged the range of measured properties. This development connected the established tasks of air-quality monitoring with questions about particles, clouds and climate, while preserving the long observational context needed to interpret new measurements.

The nearby atmospheric station at Křešín u Pacova added a major new facility. Its 250-metre mast was constructed in 2012 and the station entered operation in June 2013. Continuous greenhouse-gas monitoring, designed with participation in the Integrated Carbon Observation System in mind, was combined with additional measurements of atmospheric constituents and aerosol properties. Cooperation involved CzechGlobe, CHMI, the Institute of Chemical Process Fundamentals and Masaryk University's RECETOX centre. The decision in 2017 to establish closer coordination within the National Atmospheric Observatory Košetice gave this collaboration a clearer organisational expression. The development illustrates how a specialised research site could grow through shared facilities without requiring all participating groups to merge institutionally.

By the later part of the period, the Košetice complex connected atmospheric observations made at different heights and by different techniques. The observatory joined EARLINET on 1 November 2023, extending its involvement in European observations of aerosol vertical structure. This complemented measurements at the surface and on the tall mast. Scientifically, such combinations helped researchers distinguish changes in near-surface concentrations from differences in atmospheric transport and layering. Institutionally, they required coordination of instrument maintenance, calibration and data treatment across organisations. The research infrastructure was therefore sustained by common practices as well as by buildings and instruments, and its international usefulness depended on the comparability of the resulting observations.

Climatological priorities also changed in their balance and geographical reach. Research on circulation and climate variability continued, while the evaluation of extremes, their simulation in climate models and biometeorology became closely connected fields. The Institute of Atmospheric Physics brought these subjects into cooperation with universities, CHMI and public-health researchers. Heat and other atmospheric hazards encouraged questions about

the exposure of people and the performance of models under unusual conditions. The investigation of atmospheric mechanisms acquired additional purposes, linking an explanation of circulation or temperature variability to the circumstances in which environmental conditions become consequential for society.

Historical climatology contributed to this reassessment by extending the temporal basis of comparison. A collaborative study published in 2022 by Brázdil and colleagues analysed reconstructed temperature, precipitation and drought indices for 1501–2020, bringing documentary evidence together with instrumental observations. The author affiliations connected Masaryk University, Charles University, CzechGlobe, Mendel University and CHMI. The work illustrates both methodological continuity and a more closely connected research community. It also distinguished the geographical representativeness of reconstructed temperature from that of precipitation. Long reconstructions consequently provided context for recent conditions while retaining the differences in uncertainty and spatial variability associated with particular climatic elements.

Agricultural drought became a prominent example of research translated into an operational information service. The Czech Drought Monitor was developed during 2012–2014 through cooperation spanning research institutes, universities and the national meteorological service. The system combined satellite information, soil-water modelling driven by CHMI observations, assessments of vegetation condition and reports from people observing conditions in the field. Daily drought forecasts were added in 2016. The account published by Trnka and colleagues in 2020 makes clear that the service depended on several kinds of evidence. Its significance for institutional history lies in the way existing observation networks and agricultural expertise were connected to a continuing public product.

The PERUN programme, begun in 2020 and still under way at the end of 2025, expressed a further shift towards coordinated research on climate change and its effects in Czechia. Its scope connected climatic analysis and scenarios with drought, water systems and environmental sensitivity. Meetings reported in 2022 and 2023 brought together researchers working in different parts of the programme and representatives concerned with environmental policy. Such arrangements made cooperation a sustained part of the research design. As the programme continued beyond 2025, its later deliverables fall outside this historical account.

Access to observations acquired a more explicit public framework in 2025. CHMI explains that legislation on the public hydrometeorological service, effective from 1 January that year, established a National Database of Hydrometeorological Data and Products. The development strengthened the basis for publishing machine-readable datasets and their metadata. For researchers and students, the scientific consequence was the possibility of building analyses on more readily reusable national observations. Data availability nevertheless remained distinct from suitability for a particular investigation. Station histories, changes in instruments and the distinction between provisional and verified observations continued to matter when selecting and interpreting the material made accessible.

Viewed across 1993–2025, these developments reveal an atmospheric research system held together by continuing observation and repeated forms of cooperation. National services-

maintained measurements and operational responsibilities, Academy institutes developed specialised investigations, and universities connected research with the training of new scientists. Larger infrastructures and shared models changed the scale on which those organisations could work together. The resulting system could address events unfolding over minutes, atmospheric structure extending far above the surface and climatic variation reconstructed over centuries. Its historical achievement rested on making those different kinds of evidence usable together while preserving the scientific judgement required to recognise their respective limits.

Historical Climatology: Documentary Sources, Instrumental Records and the Reconstruction of Past Climate

Historical climatology developed in the Czech Republic between 1993 and 2025 through an increasingly close relationship between archival scholarship and quantitative climate analysis. Researchers assembled evidence from chronicles, private diaries and institutional records, then tested ways of comparing that evidence with meteorological measurements. The resulting reconstructions extended the temporal context of Czech atmospheric science far beyond the observing networks of the modern state. Their scientific value rested on the treatment of uncertainty: the conditions under which a document was written, the climatic meaning of a harvest date and the comparability of an old thermometer record all required examination before they could support an account of past climate.

The institutional setting favoured sustained work across these boundaries. At Masaryk University in Brno, Rudolf Brázdil and colleagues collaborated with historians and archivists, including Oldřich Kotyza and Hubert Valášek, while developing connections with the hydrometeorological service and international researchers. University project records show support for investigations of climate variability in 1995–1997 and reconstruction of the last millennium in 1998–2000. Later projects addressed daily weather descriptions, early measurements and comparisons between reconstructed climate and model simulations. The sequence helps explain how individual discoveries could become components of a continuing programme. It also makes clear that the post-1993 development of the field depended on maintaining historical expertise alongside climatological methods.

The publication of *History of Weather and Climate in the Czech Lands I: Period 1000–1500* by Brázdil and Kotyza in 1995 gave this programme a substantial early expression. Published through the Geographical Institute of ETH Zürich, it situated Czech evidence within an international scholarly setting. Subsequent volumes addressed different sources and periods rather than simply extending a uniform chronology. Economic records from Louny received a separate treatment in 2000, and early instrumental observations in Moravia followed in 2002. The series established a durable form for publishing the evidence on which later reconstructions would depend. These publication dates belong to the history of Czech science after independence, although the climates investigated were much older.

Documentary evidence included direct descriptions of weather and records generated by activities sensitive to it. A diary might describe persistent rain; an account book might record work required after snowfall. Interpretation depended on the author’s interests and vocabulary, sometimes in Czech, German or Latin. Brázdil and Kotyza explained the range of these sources in a Czech methodological study in 2001. A European review led by Brázdil in 2005 placed such historical interpretation within a broader climatological programme.

The diversity of written evidence made the assessment of its independence essential. Several later accounts might reproduce one original report, giving an exaggerated impression of corroboration. An unusual event could attract extensive description while an ordinary season passed almost without comment. Researchers consequently had to establish when a source was written, what locality it described and how its information related to other surviving testimony. A silence in a chronicle could not automatically be interpreted as normal weather. This attention to the production and survival of evidence remained fundamental as numerical reconstructions developed. Statistical treatment could organise documentary information, but the historical reliability of the underlying record still had to be established.

The economic documents of Louny offered a particularly instructive example. Brázdil and Kotyza’s 2000 monograph examined municipal sources from the fifteenth to seventeenth centuries. Wage accounts recorded tasks influenced by weather, including snow removal, work associated with river ice and repairs after floods. Agricultural work supplied indications of seasonal conditions. These records revealed climate through ordinary economic activity, provided that researchers understood what was being paid for and when the work occurred. The administrative purpose of a record helped explain its climatic meaning.

Private weather diaries allowed a different degree of proximity to individual observations. A study published in 2003 by Brázdil, Valášek and Jarmila Macková examined the Latin diary of Karel Bernard Hein, a parish priest at Hodonice near Znojmo. His daily entries from February 1780 to October 1789 supported the interpretation of monthly temperature and precipitation conditions. The authors compared the documentary evidence with instrumental observations and with material from Austria, Germany and Switzerland. This work demonstrated the possibilities of examining a local witness within a wider geographical context. It also showed how the description of a particular decade could contribute to methodological questions about the agreement between written and measured evidence.

Early instrumental observations required their own historical investigation. The 2002 volume on meteorological measurements in Moravia before the end of the eighteenth century, prepared by Brázdil, Valášek, Zbyněk Sviták and Macková, addressed the dispersed beginnings of measurement rather than a fully established national network. Identifying observers and recovering their records were necessary stages in making these observations accessible to climatology. The existence of numbers did not remove questions about instruments, exposure or the organisation of observation. Early measurements belonged to particular scientific and social settings, and their usefulness increased when those settings could be reconstructed. Historical climatology thus investigated the history of measurement as part of the evidence itself.

The long Prague-Klementinum series provided an especially valuable point of reference. CHMI dates the series from 1775, following earlier observations, but notes gaps in its first years and a gap-free record from January 1784. The station's history continued through changes in observational practice, including automation in 2012. For research after 1993, the significance of this record lay in the opportunity to relate documentary descriptions to observations extending across more than two centuries. Its location within a historic urban complex also made it a source that required careful contextual interpretation. Continuity in the station's name and location could coexist with changes in instruments and in the environment surrounding the measurements. Brázdil and Marie Budíková addressed one aspect of that problem in their 1999 study of the urban influence on Klementinum temperatures. By comparison with rural stations, they examined how the development of Prague's heat island affected seasonal and annual values. The strength of the urban contribution differed between seasons, and its earlier development was harder to establish where suitable homogeneous reference observations were lacking. The methodological implication was substantial. A long urban series could serve regional climate research only if the local influence was considered explicitly. Investigating that influence improved the interpretation of the record without diminishing the importance of its exceptional length.

The recovery of observations in Brno enlarged the instrumental basis beyond Prague. The 2005 monograph by Brázdil, Valášek and Macková examined meteorological activity during the first half of the nineteenth century in relation to the city's scientific organisations and individual observers. It assembled and homogenised series of pressure, temperature, precipitation and humidity, while also considering visual weather reports and extreme events. Its structure brought historical explanation into direct contact with statistical analysis. The work exemplified the labour involved in constructing a usable early series from records made by different people. A regional climate record emerged through reconstruction of the observing practice as well as through the recovery of measurements.

A more explicit framework for quantitative temperature reconstruction appeared in the study published by Petr Dobrovolný and colleagues in 2009. Documentary evidence for 1718–1850 was interpreted as monthly temperature indices on a scale from minus three to plus three. The indices could then be combined into seasonal and annual values and compared with overlapping Klementinum observations. Linear regression provided a relationship between the documentary indices and measured temperatures, with separate statistical examination of reconstruction performance. The resulting series joined reconstructed and instrumental information to cover 1718–2007. This was a methodological advance because the conversion into temperature units was accompanied by an assessment of how well the procedure reproduced observations. Calibration and verification served different purposes in this approach. Calibration estimated the relationship between a proxy and the climatic quantity being reconstructed; verification examined its performance using observations not employed in fitting that relationship. A reconstruction that appeared convincing within the fitting period could perform less well elsewhere. The 2010 European methodological synthesis by Brázdil and international collaborators emphasised this distinction and the importance of a sufficiently long overlap with instrumental data. It also discussed changes in the relationship

itself, e.g., where crop varieties or harvesting practices altered. Quantification therefore made the assumptions of reconstruction more explicit and allowed their consequences to be investigated.

The Central European temperature reconstruction published by Dobrovolný and an international team in 2010 extended this work across national borders. Documentary index series from the Czech Lands, Germany and Switzerland were combined with eleven instrumental temperature records, using an overlap during 1760–1854. The instrumental records had been corrected for sources of inhomogeneity, including inadequate protection of early thermometers from radiation and urban influences. The study reconstructed monthly, seasonal and annual temperatures back to 1500, with documentary evidence from other European regions used for cross-checking. Czech materials consequently became part of a reconstruction whose geographical meaning exceeded the national territory. International cooperation contributed both additional evidence and opportunities to test its consistency.

Reconstruction of precipitation presented different difficulties. The study by Dobrovolný, Brázdil, Trnka, Kotyza and Valášek, published in 2015, combined documentary precipitation indices with homogeneous instrumental totals to reconstruct seasonal and annual precipitation from 1501. Its calibration used the overlap during 1804–1854. Verification supported the reconstruction particularly for summer and annual values, while performance for other seasons was less consistent between parts of the overlap period. These differences mattered because a successful temperature reconstruction could not establish the reliability of a precipitation series. The work advanced knowledge while making clear that reconstruction skill depended on the variable and season under investigation.

Phenological evidence supplied another route to past climate. Martin Možný and colleagues used grape-harvest records from the Bohemian wine-growing region, principally northwest of Prague, in a reconstruction published in 2016. Their series covered 1499–2015 and targeted mean temperatures from April to August, the part of the year to which grape development was sensitive. Instrumental temperatures beginning in 1801 provided an extensive period for calibration and verification. Comparison of regression and variance-scaling methods also examined how well extremes were retained. Harvest dates could thus support a quantitative climatic interpretation, provided that the season represented by the biological response and the history of cultivation were considered carefully.

Differences between kinds of evidence became a subject of research in their own right. Petr Kolář's 2017 comparison examined instrumental temperatures and documentary and natural proxy reconstructions for Czechia during 1701–2010. The study investigated agreement in warm and cold periods, extremes and longer variations, with additional European series helping assess geographical and methodological differences. A tree-ring reconstruction contained a greater share of low-frequency variation. Such comparisons encouraged attention to the particular climatic signal represented by each record. Agreement could strengthen an interpretation, while disagreement could identify a difference in seasonality, geographical coverage or the response of the proxy rather than a simple error in one series.

Long documentary chronologies also changed the study of drought. In 2013, Brázdil and colleagues examined evidence extending from 1090 to 2012, while explicitly recognising the scarcity of material before 1500. Their treatment of the pre-instrumental period employed a defined criterion for identifying a dry year from consecutive dry months. This made the construction of the chronology more transparent. It also distinguished the existence of an early reported drought from the availability of a continuous and equally detailed climatic series. The contribution of medieval evidence depended on recognising its uneven survival, especially when comparing event frequencies across centuries with very different documentary coverage.

In 2016, further work combined reconstructed temperatures and precipitation to derive several drought indices back to 1501. These included an index based on precipitation alone and measures that also incorporated atmospheric water demand or water-balance assumptions. Their different responses helped explain how warming could intensify dryness even where precipitation totals showed no comparable trend. Comparison with tree-ring evidence and the *Old-World Drought Atlas* supplied additional checks. This development broadened historical climatology from the reconstruction of individual meteorological quantities to the assessment of their combined hydroclimatic meaning. The resulting indices nevertheless retained uncertainties inherited from the reconstructed variables and the assumptions used in their calculation.

Documentary sources preserved consequences of drought that a numerical index could describe only indirectly. A 2019 study by Brázdil and collaborators examined extreme droughts in the Czech Lands together with human responses during the pre-instrumental period. Contemporary descriptions linked dry conditions with agricultural difficulties and shortages in water-dependent activities, while recording attempts to respond to those conditions. The authors selected events using reconstructed drought indices and then interpreted them through the documentary record. This combination allowed climatic severity and social experience to be considered together. It also helped distinguish the atmospheric event from its consequences within societies whose resources and vulnerabilities differed from those of the present.

The investigation of 1531–1540 published in 2020 demonstrated the value of extending this comparison across Central Europe. Within the reconstructed Czech series for 1501–2015, those years formed the driest summer decade. Documentary evidence from neighbouring regions helped establish the wider sequence of dry episodes, interrupted by wetter or more ordinary years. The collaboration included scholars working on German, Swiss, Austrian, Hungarian and Polish evidence. Its geographical extension was significant, but the distinction between the Czech quantitative result and the broader documentary comparison remained necessary. A regional ranking derived from one reconstruction could not automatically be treated as a uniform climatic ranking for every part of Europe.

By 2022, a collaborative analysis could examine annual and seasonal temperature, precipitation and drought series for 1501–2020 within one extended framework. Brázdil, Dobrovolný and colleagues assessed their variability and their relationships with climatic influences, including volcanic activity and the North Atlantic Oscillation. The study identified

1991–2020 as the warmest and driest 30-year interval in the reconstructed series, while distinguishing relatively stable precipitation totals from increasing dryness in temperature-sensitive indices. This distinction strengthened the interpretation of recent conditions by placing them within a much longer record. It also showed why conclusions about historical dryness need to specify the climatic quantity or index being assessed.

Economic history remained a source of new questions as well as new data. The 2024 investigation of grain prices in Sušice by Brázdil, Jan Lhoták, Kateřina Chromá and Dobrovolný analysed archival series for 1725–1824 against reconstructed climate and descriptions of unusual weather. Wheat, rye, barley and oats prices were examined within a setting shaped by agriculture and wider social and political conditions. Their relationship with weather was therefore interpreted as one influence among several. The study demonstrated the possibilities of linking climatic reconstruction to economic outcomes while avoiding a direct conversion of a high price into evidence of a particular meteorological condition.

Research on public granaries supplied a further example in 2025. Brázdil and an international team analysed records from fifteen domains in the Sušice region during 1789–1849, using grain borrowing, repayments, storage and debt as indicators of harvest outcomes. They identified unusually good and bad harvest years and tested them against documentary weather evidence and reconstructed climatic series. The records therefore supported the investigation of climate through institutions established to manage agricultural insecurity. Their value depended on understanding the operation of the granaries and the meaning of recorded transactions. The work extended the range of usable archives while keeping the relationship between climatic conditions and social responses open to examination.

Another 2025 study, by Brázdil, Lhoták, Chromá and Laurent Litzenburger, investigated taxation documents from the Prácheň region in southwestern Bohemia. Records surviving for intervals within 1655–1827 described requests for relief after hailstorms, water damage and fires caused by lightning. Crucially, the administrative rules determined which kinds of damage could qualify: the range of recognised losses changed over time. The resulting chronology therefore reflected both weather and the conditions under which officials recorded its consequences. This example gave a precise historical explanation for a familiar methodological problem. An apparent change in the frequency of recorded events could arise partly from a change in the documentary system used to observe them. The same study made its datasets available in an open repository, illustrating how archival research increasingly supported the inspection and reuse of derived series. The publication of data supplemented the earlier tradition of presenting source editions and explanatory monographs. It did not eliminate the need to consult historical context: a digital entry retained the limitations of the document from which it had been extracted. For researchers and students, the important development was the opportunity to move between published interpretation and the evidence organised behind it. Reuse became more informative when the origin, coding decisions and coverage of the observations remained traceable.

The development of Czech historical climatology after 1993 can consequently be understood as a cumulative improvement in the relationship between evidence and inference. Foundational source publications made records accessible; comparisons with measurements

enabled calibrated reconstructions; later studies investigated drought, social impacts and the changing systems that produced the archives themselves. By 2025, the field combined detailed knowledge of particular witnesses and institutions with participation in international climate reconstruction. Its contribution to geographical science lay in making long temporal comparisons possible without treating the surviving past as an evenly observed dataset. The reconstructed climate and the history of its evidence remained closely connected parts of the same scientific inquiry.

Climate Variability, Atmospheric Circulation and Regional Climate Modelling

Between 1993 and 2025, Czech research on climate variability developed an increasingly close relationship between the explanation of atmospheric behaviour and the construction of regional climate scenarios. Investigators asked how circulation shaped differences between seasons and decades, how these relationships changed as the atmosphere warmed, and how reliably numerical models reproduced them. Progressively finer maps were accompanied by closer scrutiny of the processes represented by a model, the features inherited from its driving data, and the changes inferred through particular analytical methods. By the end of the period, regional modelling had become a substantial collaborative activity, accompanied by a sustained examination of uncertainty.

The published research reveals several connected concentrations of expertise. At the Institute of Atmospheric Physics of the Czech Academy of Sciences, Radan Huth, Jan Kyselý and their collaborators developed work on circulation classification, statistical downscaling and the evaluation of climate models. At Charles University, Jaroslava Kalvová, Tomáš Halenka, Eva Holtanová and Michal Belda contributed to the interpretation and development of numerical simulations. The Czech Hydrometeorological Institute supplied observational expertise and developed the Czech climate configuration of ALADIN. Research associated with Masaryk University, CzechGlobe and agricultural bioclimatology connected atmospheric variability with regional temperature, precipitation and soil-water conditions. These collaborations brought together methods whose strengths were complementary: circulation analysis supplied a physical explanation, observations established the regional evidence, and modelling examined behaviour under specified climatic conditions.

One early contribution concerned the means by which circulation patterns were identified. In 1996, Huth compared five computer-assisted classification methods, including clustering procedures and rotated principal component analysis. The study evaluated the consistency, separation and stability of the resulting groups, as well as their ability to recover predefined types. Its conclusion resisted the attraction of a universally superior method: suitability depended on the purpose of the classification. This became a recurring issue in subsequent Czech research. A catalogue of weather types was an analytical construction whose

usefulness required testing. Different classifications could divide the same pressure fields differently and consequently yield different accounts of circulation change.

Attention also extended from the frequency of circulation types to their persistence. The distinction mattered because repeated days under similar atmospheric conditions could produce a different climatic outcome from the same number of days dispersed through a season. In their 2006 study, Kyselý and Peter Domonkos examined the mean residence time of European circulation types using the Hess–Brezowsky catalogue from 1881 onwards. They identified a marked increase between the 1970s and the late 1980s and assessed it through tests for changes, trends and unusual values. The work gave persistence a clearer place in the explanation of climatic variability. Its findings concerned the historical interval examined; they did not establish that circulation would become progressively more persistent in every subsequent period.

European methodological cooperation enlarged the comparative basis of this work. Monika Cahynová and Huth's 2010 study drew on the COST733 collection of circulation classifications, applying twenty-four objective and two subjective catalogues to eight climatic variables at 21 Czech stations during 1961–1998. Changes in the occurrence of circulation types explained only part of the observed climatic trends. In several seasons, much of the change occurred within the types themselves. Thus, a day assigned to a familiar circulation category could have different temperature or humidity characteristics in a later decade. The study made an essential distinction between changing atmospheric flow and changing climatic conditions under comparable flow. It also demonstrated why conclusions should be tested across classifications rather than inferred from one favoured catalogue.

Research on large-scale modes of variability introduced a related question of definition. Lucie Pokorná and Huth's study, published in its final journal volume in 2015, compared seven indices of the North Atlantic Oscillation and their relationships with European temperature and precipitation. The indices were derived from station pressure, pressure centres or statistical patterns. Their climatic associations differed particularly strongly in summer, when the geographical configuration of the oscillation shifted. The lesson extended beyond the choice of an index. A named mode of atmospheric variability could not be assumed to represent an identical physical pattern throughout the year. Czech contributions therefore included scrutiny of the concepts used internationally to connect Atlantic circulation with European climate.

The regional observational evidence became more extensive and systematically differentiated. A study by Pavel Zahradníček, Rudolf Brázdil, Petr Štěpánek and Miroslav Trnka, appearing in the 2021 volume of the *International Journal of Climatology*, analysed temperature characteristics for 1961–2019 using 133 stations. It compared daily mean, maximum and minimum temperatures across seasons and altitude groups. Warming was widespread, but its magnitude and the behaviour of the daily temperature range varied. Particularly strong increases occurred in summer and at lower elevations. Such findings improved the observational target against which explanations and simulations could be judged. A satisfactory model needed to reproduce geographical and seasonal relationships as well as an average national temperature.

Precipitation required a different interpretation. Brázdil and colleagues' 2021 analysis used 531 rain-gauge stations to examine totals and precipitation-day counts during 1961–2019. Most linear trends in seasonal and annual totals were insignificant, although substantial variability and changes within the annual cycle remained evident. The number of precipitation days declined particularly clearly from April to June. This work discouraged a simple transfer of the temperature narrative to rainfall. Climatic change could alter the timing and occurrence of precipitation without producing a uniform trend in the annual total. For circulation research, these differences made the seasonal distribution of weather types more informative than an undifferentiated association between pressure and yearly rainfall.

A broader comparison published by Brázdil and colleagues in 2022 examined circulation and several climatic variables across the two thirty-year periods 1961–1990 and 1991–2020. Under the objective classification employed, anticyclonic types became more frequent and cyclonic types less frequent in the later period. The analysis placed these changes alongside temperature, sunshine, humidity, precipitation and wind characteristics. Its value lay in the common temporal framework, which made different aspects of regional climate comparable. The results also showed why a climatic normal required a stated reference period. A normal calculated from recent observations described conditions already influenced by considerable warming; it could not automatically stand for the conditions under which earlier scientific or practical expectations had formed.

Connections between circulation and environmental processes were investigated at a finer regional scale. Jan Řehoř and collaborators' 2021 study examined soil-drought episodes in a transect extending from central Bohemia through southern Moravia to Slovakia. SoilClim estimates for 1961–2019 were combined with precipitation and an objective circulation classification. The researchers separated the origin, continuation and ending of drought episodes. Anticyclonic conditions and reductions in precipitation-bearing types favoured their development, while the circulation associated with their ending differed. Relationships also varied between regions, particularly between central Bohemia and the areas farther east. This approach linked circulation to the sequence of an environmental event, allowing atmospheric explanation to become sensitive to both its stage of development and its location.

Statistical downscaling supplied one route from large-scale atmospheric information to local climate. Huth's 2002 comparison examined winter daily temperature at 39 stations in central and western Europe. It tested regression and other multivariate methods using pressure, geopotential height and atmospheric temperature as predictors. Performance was assessed through accuracy and the temporal and spatial structure of the reconstructed temperatures. The best method depended partly on which property was being assessed, while combining a circulation predictor with a temperature predictor proved advantageous. The experiment established a demanding standard for downscaling: reproducing average relationships was insufficient if the resulting series distorted persistence or geographical coherence. It also showed how Czech research addressed methodological problems shared by countries with different terrain and observational networks.

Dynamical downscaling pursued the same geographical problem through a numerical model of atmospheric processes over a limited domain. The Czech adaptation of ALADIN connected

this work with an established international weather-modelling system. Aleš Farda and an international team's 2010 paper compared the French ALADIN-CLIMATE and Czech ALADIN-CLIMATE/CZ configurations in experiments driven by ERA-40 reanalysis. Tests over differently sized European domains showed that spatial and temporal performance did not improve together under every configuration. The evaluation region included Bulgaria, illustrating the international geographical reach of Czech model development. The domain boundary was consequently part of the scientific experiment, with implications for how the model followed large-scale flow and developed its own regional behaviour.

The CECILIA project gave this activity a coordinated European framework during 2006–2009. Led by Charles University, it sought climate-change impact and vulnerability assessments for Central and Eastern Europe, with regional simulations at approximately ten-kilometre resolution. The scientific rationale was closely geographical: mountains, land use and regional contrasts could be inadequately represented in coarser simulations. Its scope linked modelling with hydrology, agriculture, forestry and air quality, including the industrial borderlands of Czechia, Poland and Germany. Czech leadership therefore extended beyond supplying a national case study. It involved coordinating an assessment in which the region's terrain and environmental concerns helped determine the modelling strategy and the kinds of information required from it.

Evaluation remained central to the interpretation of the resulting simulations. Petr Skalák and colleagues' 2014 comparison assessed CECILIA runs for 1961–1990 against gridded observations and the coarser ENSEMBLES simulations. The finer models captured important spatial features of temperature, and their representation of temperature variability often improved. Benefits for precipitation were more limited, while cold and wet biases remained prominent. The findings qualified any straightforward equation between resolution and reliability. Increasing spatial detail could improve one climatic characteristic while leaving another unchanged or less satisfactorily represented. The scientific advance lay partly in documenting these differences and asking whether they reflected model physics, the integration domain or the observational reference used for comparison.

The future-climate analysis published by Belda and colleagues in 2015 extended CECILIA's contribution from validation to scenario interpretation. RegCM and ALADIN-Climate downscaled simulations from ECHAM5 and ARPEGE-CLIMAT under the then widely used A1B emissions scenario, examining 2021–2050 and 2071–2100. Broad warming features followed the driving simulations, while the regional models modified local patterns. These experiments belonged to a particular generation of scenarios and model combinations. Their historical importance is best understood through the questions they made tractable: how a large-scale climate signal acquired regional structure, how alternative models represented that structure, and which differences might matter for environmental applications. They should not be treated as interchangeable with later scenario products based on different forcing assumptions.

Circulation analysis also became a means of diagnosing numerical errors. Eva Plavcová and Kyselý's 2011 evaluation examined daily temperatures and their links to large-scale flow in regional simulations over the Czech Republic. It identified biases in both the central and extreme parts of temperature distributions, together with deficiencies in the simulated daily

temperature range. Some errors were associated with excessive advection and an overrepresentation of westerly relative to easterly flow. The relative influence of regional model formulation and the driving global model also differed between summer and winter. This work brought the two research traditions into direct contact. A circulation category could help explain why a simulation was wrong, providing more physical information than an error statistic alone.

The growing availability of model ensembles made uncertainty itself a substantial research subject. Holtanová, Kalvová, Petr Pišoft and Jiří Mikšovský's 2014 study compared PRUDENCE and ENSEMBLES outputs over the Czech Republic, separating the influence of the regional model from that of its driving global model. The balance depended on the climatic variable and on whether the analysis concerned mean conditions or their projected changes. Findings for temperature did not support a general rule equally applicable to precipitation. This was a consequential refinement of regional climate assessment. A range of outcomes reflected the structure of the modelling chain, and its interpretation required attention to the particular combinations of global and regional models represented in an ensemble.

EURO-CORDEX subsequently provided a larger comparative resource for Czech applications. Štěpánek and colleagues' 2016 study used its approximately 0.11-degree simulations under RCP4.5 and RCP8.5 to investigate drought-inducing climatic conditions. Quality-controlled, homogenised station series supplied a reference for correcting model distributions before deriving relevant indices. The results linked warming and changes in precipitation occurrence with an increased potential for drought. More precipitation in some measures could coexist with longer or more damaging dry conditions. The methodological development was therefore as important as the projected direction of change: researchers compared distributions and derived environmental indicators, rather than assuming that a change in annual rainfall alone described future water stress. These were conditional projections under specified forcing pathways.

The PERUN project, initiated in 2020 and continuing beyond the end of 2025, placed regional modelling within a coordinated national investigation of climatic change and environmental sensitivity. CHMI, Charles University, the Institute of Atmospheric Physics, CzechGlobe and other partners connected model development with the preparation of scenarios and assessments of impacts. Its research design included adaptation and validation of ALADIN for climate integrations and the examination of differing responses in mountain and lowland areas. This strengthened the connection between atmospheric simulation and geographical interpretation. The project was still in progress at the historical endpoint considered here, so its significance rests on the developments and publications achieved by 2025 rather than on later completion claims.

Holtanová, Belda and Halenka's 2022 comparison of CMIP5 and CMIP6 supplied an important qualification to the new national scenarios. It examined the annual cycle of temperature and precipitation and their interannual variability, with particular attention to CNRM-ESM2-1, the global model driving the fine-resolution Czech simulation. Differences between global models and between emissions pathways were accompanied by uncertainty from internal climatic variability. For some characteristics, the spread between runs of one model with different

initial conditions was comparable to the spread across the larger ensemble. The driving simulation also differed from the ensemble median in several respects. These findings made clear why a detailed regional run needed to be interpreted alongside a wider range of plausible climatic behaviour.

The assessment was extended vertically and geographically in a 2024 paper by Holtanová, Belda, Natália Machado Crespo and Halenka. They evaluated global-model variables along the boundaries of a regional integration domain as well as near the surface within it. Radiosonde observations helped assess the reanalysis products used as references for upper-air conditions. The study found that good representation of surface climate over Czechia did not necessarily imply equally good boundary information, particularly for temperature and specific humidity. This linked regional modelling with aerological evidence in a concrete way. The atmospheric column and the surrounding domain required scrutiny because the regional model received its evolving large-scale conditions through those boundaries.

A further stage was documented in Romana Beranová and colleagues' evaluation published in the 2025 volume of *Atmospheric Research*. The ALADIN-Climate regional reanalysis used a 2.3-kilometre grid and a convection-permitting configuration. Validation for 1990–2014 considered temperature, precipitation, humidity, wind and global radiation. Significant biases remained, including overestimated winter precipitation and a tendency to reduce the daily temperature range through warmer minima and cooler maxima. The study demonstrated the value of the detailed fields while identifying limitations relevant to their use. This product represented past atmospheric conditions; it served a different purpose from a future scenario. The same modelling system could support both tasks, but the evidence required for evaluating a historical simulation remained essential to interpreting its projections.

Statistical adjustment continued alongside these advances in physical modelling. At the European Meteorological Society meeting in 2025, Marta Martínková and Martin Hanel compared bias correction and an advanced delta-change approach for precipitation from the PERUN simulations. They distinguished adjustment of model outputs using observed historical discrepancies from modification of observations using a simulated change signal. Their comparison addressed changes in variability as well as means, and highlighted difficulties in mountainous areas. Presented as conference research, it recorded a continuing methodological discussion rather than a final prescription. The appropriate treatment depended on the intended impact study, while assumptions about the transfer of historical errors or change factors into the future remained consequential.

Across 1993–2025, Czech contributions thus joined regional knowledge to questions of wider atmospheric science. Classification experiments improved the interpretation of circulation; comparative observations established how climatic changes differed by variable, season and place; numerical experiments investigated the production of regional detail. European projects and national cooperation sustained exchanges between these activities. The resulting research tradition became especially valuable where a plausible climatic explanation had to be connected with an imperfect model and an uneven observational reference. By 2025, finer simulation and more critical evaluation had advanced together, enabling researchers and

students to examine both the information in a regional climate product and the conditions under which that information could support a scientific conclusion.

Hydrometeorological Extremes, Urban Climate and the Study of Climatic Impacts

Research on hydrometeorological extremes, urban climate and climatic impacts became more closely connected in the Czech Republic between 1993 and 2025. Floods and droughts encouraged investigation of the circumstances in which unusual weather produced serious losses, while urban warming brought attention to differences in exposure within individual settlements. The resulting research extended from the statistical description of hazards to the observation and modelling of environmental stress. Its central contribution was to make the consequences of climate geographically specific. An identical rainfall total or air temperature could have different implications according to terrain, land cover, the timing of an event and the characteristics of the people or activities exposed to it.

This development drew on cooperation across an established institutional system. The Czech Hydrometeorological Institute (CHMI) provided observations, forecasting expertise and assessments of major events. Research at the Institute of Atmospheric Physics of the Czech Academy of Sciences linked statistical climatology with atmospheric mechanisms and biometeorology. Masaryk University and CzechGlobe connected climatic analysis with landscape conditions and documentary evidence, while Mendel University contributed agricultural knowledge. Urban investigations involved these organisations alongside Palacký University in Olomouc, Charles University and the Academy's Institute of Computer Science. The affiliations of the published studies reveal a research community increasingly organised around shared problems, with the methods of geography helping to connect atmospheric measurements to places and their inhabitants.

The floods of 1997 and 2002 gave the study of extremes an immediate public significance. Rudolf Brázdil's 2002 review nevertheless showed why the scientific interpretation required care. It examined precipitation, drought, floods and strong winds, drawing attention to the quality and length of the available records and to the ambiguity of some observed trends. A damaging event could establish the need for investigation without, by itself, demonstrating a long-term change in frequency. The review also connected climatic evidence with losses and protective measures. This combination of practical urgency and critical treatment of evidence remained important as Czech research acquired longer datasets and more detailed analytical tools.

Statistical regionalisation improved the basis for assessing rare precipitation. In 2007, Jan Kyselý, Jan Picek and Radan Huth used observations from seventy-eight stations during 1961–2000 to identify regions with sufficiently similar extreme-precipitation characteristics for regional frequency analysis. Clustering of site characteristics was followed by tests of homogeneity and simulation experiments, producing four regions. The approach allowed

researchers to consider information from several comparable locations when investigating events poorly represented in a short record at one station. It also preserved differences between precipitation regimes. Such work connected the estimation of rare events with the geographical organisation of rainfall, rather than assuming that one statistical relationship would serve the whole country.

Smaller and more abrupt floods demanded a different evidential approach. Brázdil and collaborators' 2024 study assembled documentary information on flash floods during 2001–2023, including 233 events affecting 424 municipalities. The database showed considerable year-to-year variability without a significant linear trend in the series examined. Analysis connected triggering rainfall with the places where concentrated runoff encountered settlement. Because small watercourses were incompletely represented by routine hydrological observations, documentary records supplied essential information about occurrence and damage. The methodological achievement lay in combining climatic and geographical evidence while retaining the limits of the database. The absence of a trend within that record did not establish an absence of changing risk over every timescale or for every kind of flooding.

The assessment of the September 2024 flood, including CHMI's preliminary report issued in April 2025, demonstrated the continued importance of detailed event reconstruction. Its findings connected the circulation associated with the Boris depression to prolonged rainfall, the state of catchments before the event and subsequent river response. Initially low soil saturation delayed the rise of water levels in affected areas, although continued extreme rainfall eventually produced severe flooding. Forecasts and warnings were examined alongside reservoir operations and protective measures. The event thus provided evidence about both atmospheric processes and the functioning of a warning and response system. Such assessments helped translate observations collected during an emergency into questions for subsequent scientific and technical investigation.

Severe convective storms extended this cooperation beyond the usual boundaries of national research. The violent tornado in southeastern Moravia on 24 June 2021 led to an international damage survey and a 2024 synthesis by Tomáš Púčik and colleagues. The investigators combined mapping of the damage path with the examination of buildings, vegetation and infrastructure, while also considering injuries, public behaviour and preparedness. Classification using the International Fujita scale required interpretation of damage in relation to the objects struck. The study showed how a rare event could generate a substantial body of knowledge through coordinated field investigation. Its treatment of warnings and societal consequences connected meteorological research with engineering and the communication of risk.

Heat-related impacts had already encouraged a comparable crossing of disciplinary boundaries. Kyselý's 2004 investigation examined mortality during Czech heat waves in 1982–2000, accounting for long-term changes and seasonal and weekly variations in death counts. It also considered the displacement of mortality, whereby deaths during a hot episode were followed by fewer deaths than expected. This required attention to the period after the event as well as to the days of extreme temperature. The study gave Czech biometeorology an explicit

population dimension. It showed that the health consequences of heat depended on the timing and duration of exposure and on the method used to distinguish an event-related change from the background pattern of mortality.

Later work examined how vulnerability itself evolved. A countrywide study by Tomáš Janoš, Joan Ballester, Pavel Čupr and Hicham Achebak, appearing in the 2024 volume of the *International Journal of Epidemiology*, analysed all-cause mortality for 1987–2019 and cause-specific mortality for 1994–2019. Regional temperature–mortality relationships were estimated with methods allowing for non-linear responses and delayed effects. Cold-related relative risks declined in many groups, whereas heat-related risk increased in the overall population and in several particularly vulnerable subgroups. The analysis also identified widening inequalities by sex and age. Its contribution was to treat adaptation as an empirical question: improvements in one part of the temperature–health relationship could coexist with increasing vulnerability elsewhere.

Documentary studies of weather-related fatalities supplied another, complementary view of climatic impacts. Brázdil and colleagues' 2021 analysis used newspaper and other records to investigate reported deaths associated with floods, wind, convective storms, precipitation, frost, heat and fog during 2000–2019. It considered the circumstances and locations of incidents, including road accidents and hazardous behaviour. These records described identifiable events and their immediate settings. They therefore answered different questions from epidemiological estimates derived from population mortality statistics. The distinction mattered when comparing results: a database of individually reported incidents could illuminate pathways of exposure without constituting a complete estimate of the health burden associated with temperature.

Agricultural drought research developed a similarly explicit interest in the mechanisms connecting climate and impact. Miroslav Trnka and colleagues' 2015 investigation of soil drying during 1961–2012 examined temperature, radiation, humidity and the seasonal availability of water. Increased evaporative demand, earlier snow disappearance and an earlier growing season helped explain why soils could lose moisture sooner. The findings connected atmospheric change with the timing of plant water use. Drought consequently became more intelligible as a developing imbalance between water supply and demand, with consequences that could intensify even where precipitation totals alone supplied an incomplete account of the change.

Petr Hlavinka and collaborators had established an important agricultural connection in their 2009 study of drought and crop-yield variability. They compared detrended yields of eight crops with an agricultural drought index across seventy-seven districts during 1961–2000. Relationships differed between crops, districts and the parts of the growing season in which water stress occurred. This made the timing of drought central to the interpretation of losses. Removing longer-term yield trends also helped distinguish interannual climatic effects from broader changes in agricultural production. The work brought regional climatology into contact with the biological requirements of particular crops, providing a more useful account of agricultural sensitivity than a single national drought indicator could offer.

Monitoring subsequently made some of this knowledge available during developing events. The Czech Drought Monitor, developed in 2012–2014 and described by Trnka and colleagues in 2020, combined satellite information, SoilClim estimates, vegetation assessments and reports from observers. Daily forecasts were added in 2016. Its scientific significance lay in bringing different observations into comparison, including information about consequences reported from the field. Soil moisture estimates could be assessed alongside crop condition and local experience. The system also connected international expertise in drought monitoring with Czech observational networks. It enabled continuing feedback between the description of an event and investigation of its environmental effects.

The relationships between hazards received more integrated treatment in Trnka and colleagues' 2016 assessment of drought, soil erosion and local flooding on agricultural land. The study approached these pressures together because the properties and management of the same landscape could influence several kinds of damage. Its geographical purpose was to identify areas where hazards overlapped and where soil condition increased susceptibility. This moved assessment towards the circumstances in which environmental stresses accumulated. It also encouraged a more careful interpretation of land management: measures intended to improve resilience needed to be examined in relation to the range of processes operating at a site.

Climatic impacts research also reached activities with a distinctive regional and economic identity. Martin Možný and an international team's 2023 investigation of European aroma hops combined observations and model projections, including evidence from Žatec in Czechia and growing regions in Germany and Slovenia. The researchers examined yield, ripening and alpha-acid content, the latter being important for brewing. The study connected warmer conditions and changing seasonal development with both the quantity and the quality of production. Its wider significance lay in extending impact analysis beyond a simple measure of harvested mass. The climatic sensitivity of a specialised crop could involve the characteristics that gave it commercial value, requiring adaptation to consider product quality alongside water availability and yield.

Urban climate research developed through a related change in the questions asked of observations. Brázdil and Marie Budíková's 1999 investigation of the Klementinum record examined the urban contribution to long-term temperature fluctuations. Subsequent work made the spatial differentiation of the city a research object in its own right. The 2012 volume *Klima Brna: Víceúrovňová analýza městského klimatu*, led by Petr Dobrovolný, combined standard observations, a dedicated station network and thermal remote sensing. It examined urban–suburban differences and their possible causes. The city was thereby investigated through several observational scales, linking the continuity of station climatology with a more detailed account of the built environment.

Mobile measurements helped reveal differences that a small number of fixed stations could miss. Dobrovolný and Lukáš Krahula's 2015 Brno study investigated nocturnal air temperatures along routes through the city under clear, relatively undisturbed conditions. Vegetation and building density were important explanatory variables, and geographical information supported interpolation beyond the measurement routes. The resulting

temperature field demonstrated that urban warmth varied with the arrangement of the landscape. Its interpretation remained tied to the selected weather conditions and time of night. This approach strengthened the geographical explanation of the heat island while showing why an intensity measured during a favourable episode should not be presented as an average for every night or season.

Internationally comparable descriptions of urban form supplied a further methodological advance. Jan Geletič and Michal Lehnert's 2016 study developed a GIS method for delineating local climate zones in Brno, Hradec Králové and Olomouc. The method used measurable characteristics of buildings and surface cover, with an explicit decision procedure. It adapted an international classification to the structure of Central European settlements and tested the resulting maps against expert delineations. Local climate zones provided a common language for comparing urban landscapes. Their value depended on how well the mapped physical properties represented each location, making classification and validation substantial components of urban climatic research.

Remote sensing added spatial coverage while also sharpening the distinction between different temperature measures. Geletič, Lehnert and Dobrovolný's 2016 comparison of Prague and Brno used Landsat and ASTER imagery to examine land-surface temperatures within local climate zones. Industrial and compact built environments generally differed from wooded areas and water surfaces. These observations concerned the temperatures of surfaces viewed by the sensors. Their relationship with the air experienced by inhabitants required separate investigation, influenced by shading, wind, surface geometry and the timing of image acquisition. The research therefore enlarged the observational basis of urban climatology while discouraging the direct substitution of a thermal satellite image for a map of human thermal exposure.

The development of detailed physical modelling brought individual streets and buildings into the analysis. Jaroslav Resler and collaborators' 2021 evaluation of PALM 6.0 used measurements in Prague-Dejvice to assess simulated meteorology, air quality and surface conditions during summer and winter episodes. The work connected the Institute of Computer Science, Charles University, CHMI and international expertise. Comparison with observations exposed limitations involving complex surfaces and their representation on the model grid. Validation became a substantial research task, providing evidence about which processes could be represented before the system was applied to changes in urban design.

Geletič and colleagues' 2022 study then examined hypothetical greening strategies in the validated Prague-Dejvice modelling domain. It compared street trees with green roofs and walls using the Universal Thermal Climate Index, which expresses the combined thermal effects of the environment on people. The simulated benefits of trees were strongly localised, particularly beneath crowns exposed to sunshine; average effects across the neighbourhood were considerably smaller. Green roofs and walls produced limited changes in pedestrian thermal exposure in the scenarios examined. This was a useful qualification for adaptation planning. The climatic effect of greenery depended on its position relative to people and surrounding buildings, and could not be inferred solely from the total area made green.

The longer temporal perspective remained essential alongside such detailed spatial experiments. A 2025 study by Zahradníček, Brázdil, Jan Řehoř, Dobrovolný and Robert Šanda examined Prague's changing temperatures and urban heat island, using long records and observations from the city and its surroundings. The urban–rural contrast was particularly pronounced for minimum temperatures, with the strongest intensification occurring in summer. Calm, sunny and anticyclonic conditions helped explain the larger differences. These findings connected regional warming with the reduced nocturnal relief experienced in urban settings. They also showed why changes in maximum, minimum and mean temperature should be distinguished when assessing how a city's climate was changing.

Across these fields, the meaning of an impact became progressively more specific. Flood reconstruction examined where rainfall was converted into dangerous flow and how warnings informed action. Agricultural studies identified sensitive stages of crop development, while urban experiments located the places where shade altered thermal exposure. Population research investigated differences in vulnerability that an average climatic index could conceal. Read together, these studies show how Czech climatic research connected physical measurements with the conditions under which they became consequential. Such connections required cooperation with specialists in soils, crops, health, buildings and public administration, extending the scientific responsibilities of climatology while preserving the need for a sound atmospheric explanation.

The growth of this research also changed the methodological knowledge available to new investigators. A field survey, a satellite product and a numerical experiment could describe different aspects of the same episode. Learning to compare them required attention to the spatial area, time interval and environmental quantity represented by each source. Czech case studies made these issues concrete, from the interpretation of damage along a tornado path to the difference between surface temperature and thermal conditions at pedestrian height. Their international usefulness rested on explicit methods and comparable observations, through which knowledge developed in particular Czech landscapes could be examined and tested elsewhere.

By 2025, the study of extremes and climatic impacts had become a sustained meeting point between atmospheric science and geographical interpretation. Major events continued to generate new investigations, but their scientific value increasingly depended on systematic comparison, dedicated observations and the examination of consequences over time. Urban research advanced from identifying a station's local influence to evaluating the climate of neighbourhoods and individual streets. Drought studies connected atmospheric demand with crops and soils, and health research revealed changing patterns of vulnerability. The history of these developments shows a field learning to explain why climatic stresses produced different outcomes in different places, and to make that explanation useful for the assessment of environmental change.

Aerology and Upper-Air Observation: Radiosondes, Vertical Atmospheric Profiles and Ozone Measurements

Between 1993 and 2025, Czech aerology developed through the renewal of an established observational programme and a widening use of its records. Balloon soundings continued to describe the atmosphere above the surface network, while ozone measurements connected national observations with international research on atmospheric composition. The principal achievement was a stronger relationship between routine measurement and scientific interpretation. Profiles originally collected for operational purposes became evidence for investigations of convection, stratospheric circulation and the reliability of reanalysis products. At the same time, the instruments and processing procedures changed sufficiently to make the history of the observations an essential part of their interpretation.

The geographical concentration of this work gave Czech aerology a distinctive institutional character. The Czech Hydrometeorological Institute (CHMI) maintained the principal civilian sounding programme at Prague-Libuš, while the Solar and Ozone Observatory in Hradec Králové specialised in radiation and ozone observations. Cooperation extended to military aerology, including the station at Prostějov, and continued with Slovak colleagues at Poprad-Gánovce. These relationships preserved technical knowledge across institutional and state boundaries. The creation of the Czech Republic in 1993 therefore altered the administrative setting of upper-air observation without inaugurating an entirely new scientific practice.

The starting equipment illustrates this continuity. Vaisala DigiCORA technology and RS80 radiosondes had been introduced at Libuš in 1992, alongside a change in the ozone sounding system. Subsequent renewal brought RS90 sondes into regular use in 1999 and RS92 equipment during the following decade; routine GPS tracking replaced the earlier dependence on LORAN-C by 2012. The station’s technical history dates routine RS41-SG measurements from December 2017. These changes affected the measurement of humidity and the determination of wind as well as the processing of the ascent. Modernisation thus changed the character of the record, even when the station name and the purpose of the launch remained familiar.

A radiosonde supplies a sequence of observations as its balloon ascends through successive atmospheric layers. Temperature and humidity measurements, together with information about position and height, allow the thermodynamic structure and wind field to be reconstructed. In the Libuš programme, balloons commonly reach approximately thirty to thirty-five kilometres, passing through the troposphere and well into the stratosphere. A sounding consequently covers a much greater vertical range than the atmospheric boundary layer that directly affects most geographical observations at the surface. It gives physical context to conditions that a ground station can record only at one level.

The profile nevertheless requires a geographical interpretation of its own. A rising balloon travels with the wind, so the observations describe a moving path through an evolving atmosphere. They are neither an instantaneous column above the launch point nor an average over Czech territory. This matters when a profile is compared with a local storm, a satellite overpass or a model grid cell. The nominal observation time also differs from the instant of

release because the ascent takes time. Such considerations explain why the apparent simplicity of a plotted temperature or wind curve conceals decisions about spatial and temporal correspondence.

Technological improvement did not remove the need to choose an observation schedule. The Libuš anniversary history records the discontinuation of the 18 UTC sounding on 1 January 2013 for economic reasons, leaving observations at 00, 06 and 12 UTC. This was a change in temporal sampling rather than an abandonment of the programme. For research, it means that a comparison across decades must consider which parts of the daily cycle remain available. A more capable sensor can improve an individual ascent while a reduced launch schedule limits the situations represented in the archive.

An application of these observations to storm research appeared in Petr Pešice, Jan Sulan and Daniela Řezáčová's 2003 investigation of convection precursors. The researchers combined Libuš soundings with radar observations during 1996–2001 and examined seventy-three significant convective events from 1998–2001. Their analysis considered instability, convective available potential energy and vertical wind shear, evaluating the probability of radar-defined precipitation categories. This connected a measured atmospheric environment with the later behaviour of storms. The scientific advance lay in testing the usefulness of the precursors against observed outcomes, rather than treating favourable index value as sufficient evidence that severe convection would occur.

This approach also clarified what upper-air observations could contribute to forecasting research. A temperature profile identifies stable layers and levels at which an ascending air parcel might become buoyant; a wind profile describes changes in speed and direction that influence storm organisation. The Czech study found substantial roles for wind shear and the form of the hodograph, which plots the changing wind vector with height. Reading these quantities together gave a more physically grounded account of convective potential. Their interpretation still depended on whether the sounding adequately represented the air mass in which the storm developed.

The use of radiosondes in climate research extended well above the storm environment. Michal Kozubek, Jan Laštovička and Peter Križan's 2014 paper compared stratospheric winds in ERA-40, ERA-Interim and NCEP/NCAR with balloon observations, including those from Prague. The comparisons addressed wind speed and direction at selected pressure levels and exposed differences that varied with period and circulation. At 10 hPa, substantial directional disagreements sometimes occurred when Prague winds came from less frequent sectors. The study demonstrated that agreement under the prevailing westerly circulation did not guarantee comparable performance in every atmospheric situation.

By the 2020s, this evaluative role also formed part of Czech research on the boundary conditions used by regional climate models. Eva Holtanová, Michal Belda, Natália Machado Crespo and Tomáš Halenka's 2024 study compared ERA5 and CFSR with radiosonde observations at four European locations before using reanalysis information to assess climate-model errors. Vertically resolved observations thus helped establish the reference against which a model could be judged. Radiosondes retained scientific importance within an

increasingly computational research environment. Their use made explicit a difficulty underlying model evaluation: a difference from a reference field required consideration of the quality of that field as well as the performance of the model.

Ozone sounding developed alongside these meteorological uses but answered a different question: how was the gas distributed with height? The Czech programme had begun before independence, with experimental launches in the 1970s and a regular winter–spring regime established in 1982. The transition to electrochemical concentration cell instruments in 1992 supplied the immediate technical foundation inherited in 1993. At Libuš, the established seasonal programme involved launches on Mondays, Wednesdays and Fridays from January to April. This concentration on winter and spring gave particular value to observations of strong stratospheric variability, while limiting their use as a description of the entire annual cycle.

An electrochemical concentration cell ozonesonde draws ambient air through a sensing solution and derives ozone from the resulting electrical current. The interpretation depends on the air flow through the pump, the background current and the response of the solution, as well as on temperature and pressure. Calibration and preparation therefore affect the scientific result before the balloon leaves the ground. The World Meteorological Organization’s ASOPOS 2.0 guidance, published in 2021, treated these relationships as an uncertainty chain. Its emphasis on preparation, processing and metadata reflected the requirements of researchers seeking small changes within records assembled from many individual launches.

The Libuš metadata revised in September 2024 provide a dated account of this continuing renewal. They record ECC5A sondes until January 1997 and ECC6A instruments thereafter, with RS41 radiosondes and DigiCORA MW41 ground equipment used in the ozone programme from 2020. They also document the adoption of ASOPOS 2.0 preparation guidance from 2022 and a humidity and temperature correction to pump flow from 2023. These dates show that improvement continued after a new instrument had entered service. Operational practice and data reduction remained subjects of revision in their own right.

The same metadata make an important distinction between measured and derived quantities. The RS41 configuration described for the Prague ozone programme has no pressure sensor: pressure is derived using GPS information within the processing system. This differs from the direct pressure measurements associated with earlier equipment. A profile can therefore contain a pressure value without that value having been obtained in the same way throughout the record. For historical analysis, the relevant unit of continuity is the complete measurement and processing procedure, rather than the name of a variable in a data file.

At Hradec Králové, total-column observations supplied a complementary perspective. The Dobson D074 instrument, operating since 1961, was joined by Brewer B098 in 1994 and Brewer B184 in 2004. A spectrophotometer estimates the total amount of ozone along the atmospheric column from the wavelength-dependent attenuation of ultraviolet radiation. It does not identify every layer contributing to that total. Conversely, a balloon profile resolves much of the vertical distribution but does not directly measure the complete column above its burst altitude. The two approaches could be compared and interpreted together, while the separation between

Hradec Králové and Prague also required attention to atmospheric variability between the sites.

The distinction between ozone in different atmospheric layers also mattered for the questions asked of these records. Stratospheric ozone absorbs ultraviolet radiation and provides a protective function, whereas ozone near the ground is an air pollutant. A total-column measurement cannot establish the concentration inhaled at a particular urban location. Equally, a surface ozone monitor cannot describe the condition of the stratospheric ozone layer. Vertical soundings help connect these domains by locating enhanced or depleted ozone within the atmosphere. They require interpretation alongside meteorological structure and transport, rather than an assumption that an increase or decrease has the same environmental meaning at every altitude.

The coexistence of Dobson and Brewer instruments made Hradec Králové valuable for methodological research. Karel Vaníček, Martin Staněk and Martin Dubrovský's 2003 CANDIDOZ report re-evaluated the Dobson record for 1961–2002 and Brewer observations for 1994–2002. It examined calibration histories, raw measurements and the calculation of daily and monthly values. Undertaken within a European research project, the work showed how international cooperation could support a detailed reassessment of national records. Its purpose was to establish what differences arose from observation and processing before drawing conclusions about changes in the atmosphere.

Vaníček's 2006 paper gave this problem wider relevance through comparisons with satellite ozone products. Seasonal differences between Dobson and Brewer monthly means at Hradec Králové reached approximately four per cent in winter and spring. Temperature-dependent ozone absorption and sulphur dioxide contributed to the discrepancies. A change of instrument could therefore produce an apparent climatic signal unless the relationship between the observing systems was understood. The study also showed why satellite validation benefited from carefully maintained ground instruments: an apparent disagreement could involve the characteristics of either observing system, rather than an error attributable in advance to one of them.

The research culminated in substantial syntheses in 2012. Vaníček, Ladislav Metelka, Pavla Skřivánková and Staněk published the Czech monograph *Dlouhodobé změny ozonové vrstvy nad územím České republiky*, bringing together evidence from the national ozone programmes. Its scope included the fifty-year perspective available from Hradec Králové and the contribution of balloon profiles from Libuš. Brewer-Umkehr observations, introduced at Hradec Králové in 2005, added an indirect method of estimating vertical ozone distribution. This retrieval used changing ultraviolet observations at large solar zenith angles to infer ozone in broad layers. Its vertical resolution and assumptions differed from those of an ascending electrochemical sonde.

In a companion data paper, the same authors constructed and compared original, corrected and merged total-ozone series for 1961–2010. A Dobson-to-Brewer transfer procedure reduced seasonal differences below the instruments' one per cent calibration limit, while reanalysis information helped fill gaps in the observational record. The resulting series were

made available through PANGAEA. The authors nevertheless found seasonal differences among datasets during 1994–2010 that could affect estimates of ozone recovery. Producing a more complete record did not settle every question about its interpretation. It provided a documented basis on which those questions could be examined.

A separate line of Czech research investigated the fine structure visible within ozone profiles. In 2005, Križan and Laštovička analysed positive and negative ozone laminae across Northern Hemisphere stations, including Prague-Libuš. These relatively narrow layers contained more or less ozone than the surrounding profile and carried information about atmospheric transport. The study identified changes in lamina characteristics around the mid-1990s and considered their relationship with circulation. This moved the analysis beyond the amount of ozone in the whole column. The shape of the profile became evidence about the processes arranging air masses vertically.

Križan's 2019 study developed that interpretation using observations from Payerne, Uccle and Legionowo. The research was undertaken at the Czech Academy of Sciences, although the station records examined were Swiss, Belgian and Polish. It distinguished laminae associated with planetary waves from those associated with gravity waves and found the former substantially more frequent under the method employed. The two groups also differed in seasonality and vertical occurrence. This was a clear example of Czech upper-air research extending through international datasets. National scientific contribution could consist in an explanatory method applied to observations collected elsewhere.

The expanding use of reanalysis made scrutiny of atmospheric composition records more necessary. Križan, Kozubek, Laštovička and Radek Lán's 2021 comparison of MERRA-2, ERA5 and JRA-55 examined ozone discontinuities during 1980–2017 with three homogeneity tests. Differences between reanalyses exceeded differences between tests within an individual reanalysis, and the incidence of discontinuities varied with altitude. The authors investigated changes associated with the satellite information assimilated into the products, while recognising that a discontinuity could also have a natural origin. Such work reinforced the value of observational programmes whose instrument histories could be examined alongside a calculated atmospheric field.

International archives made these Czech contributions accessible but also required readers to distinguish programme history from repository coverage. The Prague metadata describe a much longer observing tradition than the particular NDACC data subset beginning in January 2004. That archive date must not be mistaken for the beginning of Czech ozonesonde measurement. Deposits in NDACC and the World Ozone and Ultraviolet Radiation Data Centre, together with published datasets and processing descriptions, allowed observations to enter comparative studies beyond their original operational setting. Their usefulness depended on preserving the circumstances under which each profile had been obtained.

A 2025 study by Metelka, Martin Stráník and Staněk demonstrated the continuing value of the Hradec Králové programme for environmental interpretation. Examining erythemal ultraviolet radiation during 1996–2024, the authors found an increase associated principally with greater sunshine and global radiation, rather than a general decline in total ozone. Their modelling

separated the contributions of the available predictors. The finding cautioned against explaining a surface radiation trend through ozone alone. It also connected several decades of atmospheric composition measurements with a practical question about the changing radiation received at the ground.

Read across these studies, the training requirements of aerology become clear. Researchers must be able to prepare and assess an observation, understand the physical meaning of a vertical profile and recognise changes introduced by an instrument or algorithm. Work at Libuš and Hradec Králové also shows the importance of knowledge retained by observatory staff, while the Academy and university studies demonstrate how records acquire new scientific uses. The evidence supports a view of aerological expertise as extending from measurement practice to critical data analysis. Neither a technically successful ascent nor an extensive digital archive, taken alone, guarantees a sound historical comparison.

By the end of the period considered, Czech aerology combined a concentrated observational infrastructure with an international range of scientific applications. Its development after 1993 rested on the continuation of launches, the renewal of sensors and the repeated examination of what the resulting records could establish. Ozone research made this relationship particularly visible: detecting atmospheric change required an equally careful account of changing observation. For geography and the Earth sciences, upper-air profiles supplied the vertical explanation behind conditions experienced at the surface, while showing how processes over Czech territory were connected with circulation and composition across a much wider atmosphere.

Climate Change Research, Monitoring Systems and Scientific Support for Adaptation

Climate change research in the Czech Republic acquired a broader scientific and public purpose between 1993 and 2025. Early assessments translated global climate experiments into possible conditions for Czech landscapes. Subsequent work strengthened the observational basis, investigated ecosystem responses and developed information that could inform adaptation. This development required more than increasingly detailed projections. Researchers had to explain how an atmospheric change affected a particular place, what could be learned from monitoring and which uncertainties remained relevant to a decision. By 2025, Czech climate science supported a range of practical assessments, although the availability of knowledge and its effective application continued to develop at different rates.

The new state inherited research already organised through the National Climate Programme and cooperation among meteorologists, environmental scientists and sectoral specialists. The Czech Republic ratified the United Nations Framework Convention on Climate Change in October 1993 and submitted its first national communication in October 1994. The international review published in 1995 recorded the contribution of scientific and academic institutions to this work. Reporting supplied an institutional setting in which observations,

emissions information and assessments of possible consequences had to be brought together. Climate change thereby became a subject requiring a coordinated national account alongside investigation within individual disciplines.

Jaroslava Kalvová and Ivana Nemešová's 1997 paper on climate projections illustrates the scientific character of these early efforts. The authors established a 1961–1990 baseline and evaluated global models against observed temperature, precipitation and radiation before selecting scenarios for impact studies. The selected model variants differed in the seasonal distribution of warming and rainfall. One indicated a potentially damaging combination of warmer summers and reduced summer precipitation. These were conditional representations of a changed climate, rather than forecasts of particular years. Their value lay in making possible consequences sufficiently explicit to investigate the sensitivity of Czech environments and economic activities.

The connection between climate scenarios and environmental processes was already apparent in research on managed ecosystems. A project undertaken during 1999–2001 brought together Josef Buchtele, Nemešová, Kalvová, Dalibor Janouš and Jaroslav Rožnovský across hydrology, atmospheric science and bioclimatology. Its design linked daily climate scenarios with evapotranspiration, vegetation production and water transfer through the soil–plant–atmosphere system. Mountain forests and agricultural ecosystems supplied settings in which climatic sensitivity could be examined. The proposed adaptation measures were to follow from quantitative analysis of those processes. This provided an early example of cooperation organised around the response of an environmental system.

Methodological research also made the limits of projection more explicit. In 2005, Martin Dubrovský, Nemešová and Kalvová examined uncertainty in Czech climate scenarios derived from seven global models. Their analysis separated differences associated with model behaviour and internal variability from those involving emissions assumptions and climate sensitivity. It also considered the influence of location and the scenario construction method. For adaptation, the significance was practical: the range of possible conditions depended on several choices, not simply on a single forecast being more or less accurate. Comparing those sources helped identify which conclusions were sufficiently persistent to warrant further investigation.

Reliable observations remained necessary throughout this expansion. Petr Štěpánek, Pavel Zahradníček and Petr Skalák's 2009 methodological paper described quality control and homogenisation of Czech daily temperature and precipitation records for 1961–2007. Their approach used comparisons with neighbouring stations, statistically constructed reference series and several tests, implemented through ProClimDB and AnClim. It addressed the possibility that a change in a record originated in observation rather than climate. This was a substantial contribution to climate change research because projected impacts, estimates of recent change and evaluations of models could all depend on the same underlying station series.

The continuing public function of that observational work is visible in the climatological assessment for 2024, announced by the Czech Hydrometeorological Institute (CHMI) in

October 2025. The national mean temperature of 10.3 °C was 2.0 °C above the 1991–2020 normal and the highest in the countrywide series beginning in 1961. Such a result placed an exceptional year within an identified reference framework. It did not, by itself, quantify the long-term trend or attribute every associated impact. Regular assessments nevertheless supplied an accessible connection between accumulated station observations and the changing conditions against which adaptation was being discussed.

The development of CzechGlobe enlarged the capacity to study the mechanisms connecting climate, ecosystems and society. Its institutional history traces the Centre of Excellence established in 2010 to earlier ecosystem research and records the establishment of the Global Change Research Institute of the Czech Academy of Sciences in 2016. The work associated with Michal V. Marek and his colleagues joined previously dispersed expertise within a common research organisation. This enabled sustained investment in experimental facilities and observation sites. Climate change research acquired an infrastructure designed to investigate environmental responses over time, extending beyond projects that relied principally on existing meteorological records.

The atmospheric station at Křešín u Pacova gave this expansion a particularly visible form. Alice Dvorská and collaborators' 2015 description documented a 250-metre tower designed for greenhouse-gas, aerosol and meteorological observations. Ground measurements began in 2012, followed by vertical profile measurements in 2013. The station's height helped distinguish air influenced by near-surface processes from air above nocturnal inversions. Atmospheric concentration could therefore be interpreted with information about transport and boundary-layer structure. The station connected Czech research on global change with a broader observational problem: identifying the spatial origins and environmental significance of the air being sampled.

International coordination strengthened the value of these investments. In April 2016, the Czech Republic was admitted to the Integrated Carbon Observation System, ICOS, with CzechGlobe hosting the national contribution through CzeCOS. The accession announcement identified one atmospheric station and three ecosystem stations entering the network. Membership placed observations collected within Czech territory in a shared European setting. Its scientific importance extended beyond additional sites on a map. Comparable measurements and coordinated data provision made it possible to relate local records to atmospheric and ecosystem behaviour across a larger region, while retaining the distinct conditions at each observing site.

Ecosystem stations supplied a different quantity from the concentration measured in the air above a region. Eddy covariance estimates the exchange of carbon dioxide, water vapour and energy between an ecosystem and the atmosphere by relating rapid fluctuations in vertical air movement to fluctuations in the transported quantity. CzechGlobe's distributed network included contrasting forests, wetlands and agricultural settings, with sites such as Bílý Kříž, Štítná, Třeboň, Lanžhot and Domanínek. These observations made ecosystem function measurable through seasons and unusual events. They also linked climatic exposure with processes that matter for adaptation, including water use, productivity and the persistence of carbon uptake.

A study by Natalia Kowalska, Ladislav Šigut and colleagues, published in 2020, shows why several kinds of measurement were needed. At the Lanžhot floodplain forest, the researchers examined carbon uptake using eddy covariance alongside stem-radius variations measured with dendrometers. Their initial expectation that the 2018 summer drought would have the strongest negative effect on the annual carbon and water budgets was not supported. Physiological stress and the balance accumulated over a whole year required separate examination. This finding qualified a simple equation between an exceptional dry episode and annual ecosystem performance, demonstrating the value of sustained observation around the event.

Forest research also connected adaptation with national carbon accounting. Emil Cienciala and Jan Melichar's 2024 analysis examined the consequences of drought-related conifer dieback and bark-beetle damage for Czech forest carbon stocks. A nationally calibrated carbon-budget model was used to compare management and disturbance scenarios to 2070. The study considered changes in tree composition alongside harvesting and carbon accumulation. Its estimates described conditional futures, including a possible return towards net carbon uptake; they were not observations that recovery had already occurred. The work showed why adaptation in forestry could alter both ecosystem resilience and the contribution of forests to climate mitigation.

Experimental infrastructure added a means of examining responses that could not be isolated from observation alone. Through CzeCOS, researchers could combine controlled manipulation of environmental factors with physiological measurements, biochemical analysis and remote sensing. Such facilities allowed particular mechanisms to be investigated while field stations described behaviour under actual conditions. Their relationship was scientifically productive because an observed response might otherwise have several plausible causes. Open access arrangements also made facilities available to external research teams. The infrastructure consequently supported cooperation around common methods and experimental questions, as well as the accumulation of longer records at established sites.

Czech participation in European ecosystem experimentation acquired a further institutional role in December 2023, when CzechGlobe became the host of the Interface and Synthesis Centre within AnaEE-ERIC. The centre was intended to help integrate and synthesise results from ecosystem experiments across Europe. This represented a development in the organisation of scientific knowledge as well as in equipment. Experiments conducted under different environmental conditions could inform broader questions about ecosystem response, provided that their methods and assumptions were understood. Brno thus became a point at which experimental evidence from several locations could be brought into a common scientific discussion.

Monitoring systems increasingly translated research into information available during an unfolding environmental stress. The Czech Drought Monitor, developed during 2012–2014 and described by Miroslav Trnka and collaborators in 2020, combined SoilClim modelling with satellite information and reports from observers. Its design linked meteorological input with soil-water estimates, vegetation condition and reported impacts. The combination was

important because a modelled deficit and a farmer's experience represented different parts of the same event. Bringing them together allowed the interpretation of drought to be checked against conditions on the ground and gave researchers information about where atmospheric anomalies became consequential.

HAMR extended this approach towards water management. Adam Vizina, Martin Hanel, Trnka and Jan Daňhelka's 2020 description distinguished a drought, understood as a temporary reduction in water availability, from water scarcity relative to demand. The system combined meteorological, agronomic and hydrological assessments with information about water use, drawing on models including SoilClim and BILAN. Its maps and forecasts were organised around water bodies and relevant management information. This supplied a direct connection between monitoring and decisions, while recognising that similar climatic conditions could have different consequences where demand, storage or the availability of alternative supplies differed.

These systems also clarified the relationship between early warning and adaptation. Information about the coming days or weeks could support immediate action, whereas decisions about a forest stand or water-supply system involved much longer commitments. An operational warning service could contribute observations and experience relevant to those decisions, but its success did not establish that a landscape had become less vulnerable over decades. The distinction follows from the different timescales represented by the research. Adaptation assessment required investigators to consider how a measure changed future exposure or sensitivity, as well as how well an imminent event had been described.

A more explicit national demand for such assessments developed through adaptation planning. The government adopted the national adaptation strategy in 2015 and its first action plan in 2017; both were updated in 2021. The eighth national communication, prepared in 2022, records the use of updated evidence on impacts, vulnerability and sources of risk in this revision. Scientific support therefore involved translating research into an account that could be used across sectors. The same climatic development had to be considered in relation to forests, agriculture, settlements and water management, with attention to interactions among their proposed responses.

The monitoring of vulnerability gave this work a wider evidential basis. In 2016, CENIA and the Environment Centre of Charles University developed a set of ninety-eight indicators during preparation of the action plan. CENIA's first assessment followed in 2017 using reference data for 2014, and an update undertaken in 2019 used data for 2017. This chronology distinguished the year being assessed from the year of analysis. The indicator approach also brought social and environmental information into the same discussion. Its interpretation required care because a changing indicator might describe climatic pressure, the condition of an exposed system or its capacity to respond.

At the urban scale, participatory research helped determine which questions an adaptation assessment should answer. Eliška Krkoška Lorencová and colleagues' 2018 study combined scientific analysis with stakeholder involvement in Prague, Brno and Pilsen. Participants helped identify and prioritise climate risks, while spatial assessment examined potential

heatwave impacts under a baseline and future scenarios. Comparisons were made both within individual cities and between them. The work connected climatic exposure with locally relevant concerns and provided material for planning. Participation was part of the production of useful knowledge, rather than simply a way of presenting a completed scientific map.

Research on public perception examined a related condition of adaptation. A 2019 study by Krkoška Lorencová, Blanka Loučková and Dava Vačkářů analysed a national online survey conducted in October 2014 among 1,024 respondents aged eighteen to sixty-five. Age, gender and previous experience of extreme weather were associated with differences in beliefs and action. Respondents who reported such experience were more likely to report adaptation or mitigation measures. These relationships did not establish a simple causal sequence. They showed that scientific communication operated within a society whose understanding and responses varied, making public attitudes a legitimate subject of climate change research.

Integrated assessment also extended beyond the borders of the country. Lamprini Papadimitriou, Trnka, Paula Harrison and Ian Holman's 2019 study examined interactions among agriculture, water, forestry, land use and biodiversity within a European modelling framework. Under many of the scenarios, greater agricultural competitiveness in Czechia was associated with land-use changes that could increase water scarcity and reduce biodiversity. The finding demonstrated why a possible benefit within one activity could create pressure elsewhere. Adaptation research needed to consider connections through markets and land allocation alongside the physical climate experienced within national territory.

The PERUN project, launched in 2020 and continuing beyond 2025, brought several of these scientific responsibilities into a coordinated national programme. Led by CHMI and supported through the Technology Agency's environmental research programme, it connected atmospheric modelling with the assessment of environmental sensitivity and risk. Partners included Charles University, the Institute of Atmospheric Physics, CzechGlobe, the Czech Geological Survey and the T. G. Masaryk Water Research Institute. Its research design linked national scenarios with questions arising in particular landscapes and systems. The project was still under way at the endpoint of this history, so planned results must be distinguished from those already available.

The programme's work on rainfall illustrates the practical meaning of scientific support. Research tasks included regional estimates of design rainfall and intensity–duration–frequency relationships, which connect rainfall intensity with event duration and recurrence. These quantities provide inputs for drainage design and the assessment of runoff-related hazards. Their use requires attention to the observational record and to possible changes in the conditions represented by that record. PERUN also included communication through publications, seminars and public information. Such work connected the production of technical evidence with the ability of intended users to interpret it.

The ClimRisk portal, presented by CzechGlobe in February 2024, made a further contribution to access. It provided climate information for Czech cadastral areas, with national products at 500-metre resolution and a coarser Central European view. Its design represented several models and emissions pathways and allowed users to examine uncertainty alongside a central

estimate. This made scenario information easier to obtain for local planning and investment assessment. The detail of a map nevertheless had to be understood in relation to the models and processing behind it. A fine grid improved geographical presentation without making the future climate of every individual parcel precisely knowable.

DendroNetwork supplied another form of accessible evidence in 2025. Developed through cooperation between CzechGlobe and Masaryk University's Institute of Computer Science, the system combined measurements of tree-stem variation with meteorological information and modelling. The announcement described maps updated every twelve hours at 500-metre resolution, based on measured tree responses extrapolated to the national scale. Jan Krejza's team connected the recent condition of forest ecosystems with longer records. This made the distinction between direct observation and spatial inference particularly important. The national maps offered evidence about forest stress and vitality, while the measurements themselves remained located at individual monitored trees.

The national adaptation report published in 2025 brought implementation into the assessment alongside climatic risk. It documented progress in monitoring and warning systems but also incomplete tasks and limitations in institutional capacity. In discussing research support, the report identified staffing constraints affecting the transfer of knowledge into spatial planning. This exposed a continuing difficulty in the relationship between science and adaptation: an available dataset or method required an organisation able to use it. Assessing scientific support therefore involved examining how evidence entered practice and whether the intended users possessed the expertise and resources needed to act upon it.

Across 1993–2025, Czech climate change research developed from early scenario and sensitivity studies into a field supported by substantial observational and experimental infrastructure. Its contribution to adaptation became more specific as researchers examined mechanisms, compared alternative futures and worked with the people responsible for decisions. The same development made the critical interpretation of evidence more important. An anticipated impact called for different judgement from an observed outcome, and the completion of a plan still required assessment of what it achieved. Through this increasingly critical use of evidence, climate science strengthened its place within Czech geographical and environmental research and its capacity to support the long-term care of landscapes and settlements.

Major Achievements, Research Centres, Leading Scientists and Landmark Publications in Atmospheric Sciences

Between 1993 and 2025, Czech atmospheric scientists developed several distinctive bodies of knowledge. These included longer and more dependable climate records, methods for interpreting atmospheric circulation, numerical systems for forecasting weather, and evidence connecting climatic conditions with ecosystems and human health. Some results appeared in substantial Czech monographs; others emerged through international articles and shared

research infrastructure. The following selection considers contributions that joined a scientific problem with a reusable method, an enduring observational resource or a substantial synthesis of knowledge.

The institutional geography of these contributions was concentrated but interconnected. In Prague, the Czech Hydrometeorological Institute combined observation and operational responsibilities, the Institute of Atmospheric Physics of the Czech Academy of Sciences pursued atmospheric processes and variability, and Charles University sustained university teaching and research in atmospheric physics and climatology. Brno brought together historical and geographical climatology at Masaryk University, bioclimatology at Mendel University and the developing ecosystem research infrastructure of CzechGlobe. Palacký University in Olomouc contributed local climatology, urban studies and cartographic expertise. Hradec Králové, Prague-Libuš and the Košetice–Křešín area illustrate another important feature: nationally significant science also depended on specialised observing sites outside the principal university departments.

A representative national synthesis was the bilingual *Atlas podnebí Česka*, or *Climate Atlas of Czechia*, published in 2007 by the Czech Hydrometeorological Institute and Palacký University. Its production team included Radim Tolasz, Taťána Míková, Anna Valeriánová and Vít Voženílek, bringing climatological interpretation into contact with cartographic design. The atlas made the spatial organisation of climate legible across a country whose modest area contains pronounced differences in elevation, exposure and regional setting. Its significance for geographical science lies in this act of synthesis: station measurements become evidence about territory when they are critically assembled, mapped and explained.

Such syntheses rested on less conspicuous methodological labour. Petr Štěpánek, Pavel Zahradníček and Pavel Skalák described quality control and homogenisation of Czech temperature and precipitation series in a 2009 paper covering observations from 1961 to 2007. Their subject was essential to the interpretation of subsequent change. A discontinuity caused by a station move, altered exposure or a change in measurement practice must be distinguished from a climatic signal. The scientific contribution of this work therefore extends beyond the individual series examined: it establishes the conditions under which observations can support comparisons across space and time. The reliability of a climatic conclusion begins well before a trend is calculated.

Historical climatology provided a particularly distinctive Czech contribution to European scholarship. Rudolf Brázdil, working from the Brno geographical tradition, helped to develop documentary evidence into a systematic source for climate research and the study of environmental extremes. The 2005 review Historical Climatology in Europe—The State of the Art, written with Christian Pfister, Heinz Wanner, Hans von Storch and Jürg Luterbacher, assembled an explicitly international assessment of the field. Its importance lay in connecting the interpretation of historical documents with questions recognisable to climatologists, while retaining an awareness of the societies that produced those documents. Czech research consequently participated in shaping the methodological conversation as well as supplying regional evidence.

Petr Dobrovolný's work exemplifies the analytical development of this school. The 2010 reconstruction of monthly, seasonal and annual Central European temperatures since 1500, prepared with an international team, brought documentary evidence and instrumental observations into a common framework. The achievement was more demanding than extending a graph backwards. Different sources required assessment, calibration and consideration of uncertainty before they could be combined. This publication offers a useful example of how a regional research tradition can address a larger European problem: the historical depth available in individual territories becomes scientifically more valuable when the records are compared through a shared and explicit method.

A different methodological strength developed around atmospheric circulation at the Institute of Atmospheric Physics. Radan Huth's research examined how large-scale pressure patterns are classified and how those classifications help to explain local and regional climate. The 2008 review Classifications of Atmospheric Circulation Patterns: Recent Advances and Applications, co-authored with an international group that included Monika Cahynová and Jan Kyselý, considered subjective, hybrid and objective approaches. Its broader contribution was to make the classification procedure itself an object of scrutiny. A circulation catalogue is a scientific construction whose assumptions influence the results; it cannot simply be treated as an unquestioned description of the atmosphere.

Huth's 2002 study Statistical Downscaling of Daily Temperature in Central Europe represents a related contribution at the interface between atmospheric dynamics and regional application. Statistical downscaling estimates local conditions from relationships with larger-scale atmospheric variables. The scientific difficulty lies in choosing predictors and statistical relationships that remain physically and empirically defensible. This line of work helped to frame a problem that continued throughout the period: information from a large-scale model must be translated carefully before it can answer a question about a particular place.

The development of climate-change research can be traced through the contributions of Jaroslava Kalvová and Irena Nemešová. Their 1997 paper Projections of Climate Change for the Czech Republic belongs to the early post-1993 effort to connect international climate modelling with national conditions. Its historical value lies partly in establishing a framework for questions that later became routine: how a global signal might appear regionally, what assumptions underlie a scenario, and how much confidence should be placed in its detail. Their contribution forms an important part of this intellectual history, alongside the later expansion of modelling infrastructure and project networks.

Subsequent work at Charles University maintained this concern with the credibility of regional information. Tomáš Halenka, Eva Holtanová and Michal Belda contributed to research on regional simulations, their driving global models and the interpretation of projected change. A 2024 study by Holtanová and colleagues investigated the relationship between errors in global models at regional-model boundary zones and errors within the Central European interior. The question is methodologically important because a regional model inherits information from outside its own domain. Greater spatial detail must therefore be evaluated alongside the quality of the atmospheric conditions imposed at its boundaries.

Operational numerical weather prediction supplied a further area of Czech achievement. Within the ALADIN and RC LACE cooperation, Prague became a centre of both operational work and research in 1998, during a centralised phase led by Radmila Brožková. Researchers from participating national services spent extended periods at the Czech Hydrometeorological Institute. This arrangement made scientific responsibility tangible: a model had to function reliably each day while its components continued to develop. Brožková's contribution should be understood within that combination of numerical research, coordination and operational accountability. For a relatively small national community, sustained participation in shared model development offered a practicable route to maintaining substantial expertise.

The 2018 article 27 Years of Regional Cooperation for Limited Area Modelling in Central Europe provides a collective account of this experience. Its authors included Brožková, Petra Smolíková, Oldřich Španiel, Alena Trojáková and Ján Mašek among a wider international team. As a landmark publication, its interest is institutional as well as technical: it shows how research capacity was maintained through cooperation between meteorological services. The model system was a shared scientific undertaking, requiring continuing work on its formulation, implementation and evaluation. This history also places Czech achievements within the French and Central European partnerships through which they were produced.

The connection between weather prediction and climate research remained productive at the end of the period. A 2025 paper by Romana Beranová, Belda, Brožková, Lenka Pokorná, Jitka Popová, Zuzana Rulfová and Zbyněk Sokol evaluated an ALADIN-climate reanalysis over Central Europe at a horizontal spacing of 2.3 kilometres. It examined several meteorological variables against observational evidence. For the history of the field, the publication illustrates the convergence of expertise from different institutions around a demanding common task. The scientific result consists in the evaluated behaviour of the simulation; a fine computational grid becomes useful only when its representation of observed conditions has been examined.

Physical meteorology retained a substantial place alongside these developments. *Fyzika oblaků a srážek*, or *Physics of Clouds and Precipitation*, published in 2007 by Daniela Řezáčová, Petr Novák, Miloslav Kašpar and Martin Setvák, offered an extensive Czech synthesis of cloud and precipitation processes. Its coverage connected physical explanation with severe weather and the interpretation of radar and satellite observations. The book deserves attention as a form of accumulated scientific expertise that can be passed to new researchers. Understanding the growth of a cloud, the production of precipitation and the structure of a storm remains necessary even when observations and model output arrive through increasingly sophisticated digital systems.

Research by Sokol and Petr Zacharov illustrates how this physical understanding entered forecast development. Their 2012 paper on nowcasting compared the assimilation of observed radar reflectivity with an approach that also assimilated extrapolated reflectivity into the COSMO model. In the convective cases examined, adding extrapolated information improved precipitation forecasts, with useful performance in the first two forecast hours. The limits of the experiment matter: these were evaluated cases rather than a universal guarantee of forecast skill. Its methodological contribution was to bring the immediate evolution visible in

radar observations into closer contact with the dynamical evolution calculated by a numerical model.

Jan Kyselý also helped to extend atmospheric research towards human consequences. His 2004 study Mortality and Displaced Mortality during Heat Waves in the Czech Republic examined both excess deaths during hot periods and the possibility of reduced mortality afterwards. Adjustments for longer-term and calendar-related variation were necessary before the effects of heat could be interpreted. The paper is significant because it treated a meteorological extreme as a population-health question requiring statistical care. It exemplifies a wider change in research priorities after 1993: describing the weather event increasingly formed the starting point for investigating who was affected, by how much and over what period.

Urban climatology offered another route between atmospheric processes and lived environments. The 2012 monograph *Klima Brna: Víceúrovňová analýza městského klimatu*, prepared by Dobrovolný and a substantial collaborative team, examined Brno through a multilevel approach to urban climate. The publication joined the strengths of geographical climatology with the practical complexity of a large city. It also demonstrates why the history of a research school cannot be represented by a single speciality. The Brno community that contributed to long historical reconstructions also investigated contemporary spatial differences within an urban environment, where relief, buildings and land cover interact over much shorter distances.

Olomouc developed a related body of research around Miroslav Vysoudil and, subsequently, colleagues including Michal Lehnert and Jan Geletič. The 2012 book *Podnebí Olomouce* gave the city a dedicated climatic synthesis. Later work connected detailed knowledge of particular urban areas with methods that could support comparison between cities. Geletič and Lehnert's 2016 study of GIS-based delineation of local climate zones is especially relevant here. It addressed how urban areas could be classified according to characteristics meaningful for climate research. Such classifications provide a basis for asking whether differences arise from the broader regional climate, the physical form of neighbourhoods or the observational approach employed.

The move towards physically detailed urban simulation brought further institutional connections. The 2021 validation of the PALM model system in Prague's Dejvice district, led by Jaroslav Resler and a large team including Karel Eben, Geletič and Charles University researchers, combined atmospheric modelling with computational expertise and field evidence. The study belongs to a different scale of enquiry from a regional climate simulation: streets, buildings and the immediate urban atmosphere become central. Its importance lies in confronting a complex model with conditions in an actual city. The collaboration also widened the institutional setting of atmospheric research through the participation of the Academy's Institute of Computer *Science*.

Aerology and ozone research produced achievements whose value depended on continuity over decades. Karel Vaníček, Ladislav Metelka, Petra Skřivánková and Martin Staněk contributed to maintaining and interpreting Czech ozone observations. Their 2012 monograph

Dlouhodobé změny ozonové vrstvy nad územím České republiky assembled a national account of long-term ozone-layer change. The relationship between the Hradec Králové observing tradition and aerological work at Prague-Libuš gave this research complementary forms of evidence. Total-column measurements and vertical ozone profiles answer different questions, and their respective strengths must be preserved when results are combined. An enduring observing programme is therefore a scientific achievement with its own methodological demands.

A second 2012 publication by the same team compared original and merged Dobson, Brewer and reanalysis total-ozone datasets for Hradec Králové over 1961–2010. Published in *Earth System Science Data*, it made the evaluation of the record an explicit research product. Its significance extends beyond identifying differences between instruments or datasets. Studies of long-term atmospheric change require confidence that changes in measurement technology have not been mistaken for changes in the atmosphere itself. This example also shows how work at a national observatory can become relevant to international research through clearly documented data comparison and assessment.

Czech atmospheric science also extended well above the heights reached by routine radiosondes. Jan Laštovička's work at the Institute of Atmospheric Physics connected the mesosphere, thermosphere and ionosphere with the study of long-term environmental change. The 2006 *Science* article Global Change in the Upper Atmosphere, written with Rashid Akmaev, Gufran Beig, Jürgen Bremer and John Emmert, presented this subject to a broad scientific readership. Laštovička's 2023 review subsequently assessed progress and unresolved problems. These publications explain why atmospheric change cannot be represented by a uniform warming throughout the air column: enhanced infrared cooling is important in the rarefied upper atmosphere, while dynamics and natural variability complicate the identification of trends.

The expansion of CzechGlobe added a further research centre with a different organising question: how global environmental change operates through ecosystems. The centre established in 2010 developed into the Global Change Research Institute of the Czech Academy of Sciences in 2016. Michal V. Marek and Dalibor Janouš belong to the scientific and institutional history of this development, linking ecophysiological research with the construction of a broader research environment. For atmospheric science, the importance of the centre lay in bringing meteorological conditions into sustained relation with carbon exchange, vegetation and ecosystem functioning. The resulting research territory crossed conventional departmental boundaries while retaining the need for precise observations and controlled comparison.

The atmospheric station at Křešín u Pacova illustrates the observational side of this expansion. A 2015 paper led by Adéla Dvorská described the station as infrastructure for studying greenhouse gases, aerosols and air quality. Its 250-metre tower made measurements at several heights possible within a wider Central European research setting. Such a facility contributes a different kind of scientific resource from a short field campaign: observations can be maintained and interpreted alongside changing atmospheric transport and surface

influences. Instruments create opportunities, but the scientific value of the site depends on measurement practice, analysis and the continuity of the research programme.

Agricultural drought research connected this environmental approach with the bioclimatological expertise of Mendel University and cooperating institutions. Miroslav Trnka and Zdeněk Žalud, together with researchers including Petr Hlavinka and Daniela Semerádová, contributed to the development of methods linking weather, soil water and vegetation. The 2020 article on the Czech Drought Monitor System documented a substantial collective result: monitoring and forecasting that combined modelling with satellite information and reports of local impacts. Its significance lies in the connection between physically calculated water conditions and evidence from the people observing affected landscapes. Drought thereby became an operationally monitored process with spatially differentiated consequences, rather than a label attached only after damage had occurred.

Scientific synthesis also depended on maintaining a precise professional language. The *Meteorologický slovník výkladový a terminologický*, published in 1993 under the leadership of Bořivoj Sobíšek, provides a revealing point of continuity at the beginning of the period. Its subsequent electronic development required both expert revision and technical work. Řezáčová, Miloslav Müller and Zacharov were among those associated with the renewed terminology programme. Müller, Barbora Kocánová and Zacharov's 2022 review Meteorological Glossaries and Dictionaries: A Review of Their History and Current State placed this work in an international and historical context. Definitions matter because comparable observations and reproducible methods depend partly on researchers understanding the same term in the same way.

Taken together, these publications reveal several forms of scientific leadership. Brázdil's contribution involved the development of a historical research programme; Huth's involved methodological interrogation of circulation and downscaling; Brožková's combined model development with international operational cooperation. Other forms are visible in observational stewardship, the preparation of large syntheses and the building of experimental infrastructure. These contributions are not interchangeable, and publication counts alone would give an incomplete account of their value. The examples also show how individual achievement depended on colleagues with different expertise, including station observers, data specialists, programmers, cartographers and researchers able to move between disciplinary languages.

The record from 1993 to 2025 therefore points to a research community whose strongest contributions often arose where established expertise met a new question. Documentary research supported climate reconstruction; national observations supported European comparisons; physical meteorology informed forecast methods; and urban and ecosystem studies connected atmospheric processes with consequential differences between places. The remaining scientific work followed from these achievements as much as from their limitations: records needed extending, models required further evaluation, and useful applications demanded continued contact with observations. For new researchers, this history offers a practical standard of scholarship. A contribution becomes durable when others can understand its assumptions, examine its evidence and build upon its results.

Part Seven

Hydrology, Hydrogeology and Water Research

Hydrological Research after 1993: Scientific Continuity, New Challenges and Methodological Development

Hydrological research in the Czech Republic after 1993 developed through the renewal of an established scientific tradition. River gauging, catchment studies, groundwater observation and hydraulic investigation already provided a substantial foundation when the independent state was formed. Over the following three decades, researchers used this inheritance to address questions sharpened by destructive floods, prolonged droughts and changing expectations of environmental protection. The principal methodological change was the closer connection of observations with explanations of how catchments function. By 2025, forecasting systems, field experiments and spatial models were examining different parts of the same problem: how water moves through a landscape whose climatic conditions and human uses continue to change.

The geographical setting gave these questions a particular urgency. Czech territory includes headwaters draining towards the North, Baltic and Black seas, through the Elbe, Oder and Danube river systems. Differences between mountain source areas, uplands and lower basins produce contrasting combinations of snow storage, soil moisture, groundwater recharge and runoff. Water retained during one season may sustain river flow during another, while intense rainfall can connect hillslopes and channels within hours. These relationships made the catchment an enduring unit of research. They also ensured that a national programme of hydrology had to remain attentive to processes and consequences extending beyond the state frontier.

Institutional continuity was substantial, although responsibilities and organisational forms changed. The Czech Hydrometeorological Institute maintained the national observational and forecasting framework. The T. G. Masaryk Water Research Institute, transferred to the Ministry of the Environment after 1989, operated as its contributory organisation from 1993 and became a public research institution in 2007. University departments contributed geographical, engineering and environmental approaches, while the Academy's Institute of Hydrodynamics sustained research connecting soil water and runoff processes. The combination mattered more than any simple division between basic and applied science. Field measurements could inform a methodological paper, enter a national assessment and eventually support a decision about water use or flood protection.

Continuity also resided in the records themselves. A discharge series assembled before 1993 remained indispensable to research conducted afterwards, provided that changes in instruments, river channels and measurement conditions were understood. Reservoir operation, abstraction and other interventions could further complicate the interpretation of

an apparent hydrological change. The inherited record therefore required continuing scientific attention. Measurements had to be checked and placed in their observational and catchment context before they could support a comparison between periods. This remained a common requirement across increasingly different kinds of research, from the statistical analysis of low flows to the evaluation of a numerical forecast.

The Senotín pilot project provides an early example of research directed towards landscape repair. Conducted between 1993 and 2000, it examined a small headwater area in the Novobystřická Vysočina Highland that had previously been drained and ploughed. Interventions in 1995 interrupted the tile-drainage system and modified pathways of surface and subsurface runoff. Miroslav Tesař, Miloslav Šír and their colleagues later analysed the retention and runoff response of the restored area. The study, which also involved Slovak hydrologist Ľubomír Lichner, illustrates both continuing cooperation and a changing research purpose. Earlier alterations of the landscape became experimental questions about how storage and the timing of runoff might be modified.

Access to spatial information changed more gradually than a retrospective account of the digital transition might suggest. A 2022 account by Petr Šercl and colleagues traces early GIS development in the Hydrometeorological Institute to an international project operating in 1993–1997. During the first years, equipment and expertise were concentrated in a single workplace; the completion of an institute-wide computer network in 1996–1997 helped to extend their use. Mapping catchment boundaries subsequently became part of a shared analytical infrastructure. This history shows that methodological renewal depended on practical arrangements for collecting, distributing and maintaining data, as well as on the availability of software.

International modelling research was already contributing new approaches during the 1990s. Šárka Blažková and Keith Beven’s 1997 study used a stochastic rainfall model together with TOPMODEL to investigate flood frequency in three small Jizera Mountains catchments with limited data. Simulated rainfall sequences allowed the researchers to explore events beyond the short observational record, while comparisons with measured information constrained the calculation. The study also demonstrated sensitivity to the particular sequence of storms generated. It thus addressed two questions together: how modelling could extend available evidence, and how uncertainty persisted within that extension. These questions remained relevant as later models acquired greater spatial detail.

The July 1997 flood accelerated the development of operational forecasting, and the August 2002 floods gave further force to the demand for dependable information. The scientific problem involved connecting rainfall and temperature inputs with the changing condition of a catchment and the subsequent passage of water through a river network. Forecasting systems could produce a sequence of future discharges rather than a prediction for a single moment. During the early 2000s, AquaLog was used in the Elbe basin and HYDROG in the Morava and Oder basins. Their development strengthened the working relationship between meteorology and hydrology, since the usefulness of a runoff forecast depended partly on rain that had yet to fall.

Routine model forecasts were being issued across the institute's forecasting offices from 2002. Evaluation consequently became a research task in its own right. Tomáš Vlasák and Jan Daňhelka's 2010 assessment examined operational AquaLog forecasts for the Elbe basin over 2002–2008. It considered the combined performance of observations, input preparation, weather forecasts, hydrological calculation and forecaster intervention. This was a demanding form of verification because users encountered the product of the whole forecasting process. A model's satisfactory performance with observed rainfall could not by itself establish the reliability of a forecast produced before that rainfall was known.

The floods also stimulated geographical investigation of how landscapes had been modified. Jakub Langhammer and Vít Vilímek's study of the Otava basin examined land use, drainage, river-network shortening and alterations of streams and floodplains in relation to the August 2002 event. Historical maps, remote sensing, GIS information and field mapping supplied complementary evidence. Such work expanded the analysis beyond a hydrograph at a gauging station. It also required care with spatial scale: a change that modifies a local flow pathway cannot automatically explain the magnitude of a major regional flood. The landscape became a subject of causal investigation rather than a passive background to the event.

European integration added a further set of research demands. The Ministry of the Environment's 2004 publication on implementing the Water Framework Directive described a programme organised around river basins, pressures, impacts and the status of waters. For hydrological research, this created a stronger need to connect flow regimes with the condition of water bodies and the consequences of human activity. Quantity, quality and ecological functioning increasingly had to be considered together. The importance of this change was methodological as well as administrative: assessing a catchment required compatible information from fields whose measurements and spatial units had often developed separately.

Research into the less visible parts of runoff generation continued alongside these national programmes. At the Czech Technical University in Prague, Tomáš Vogel, Martin Šanda, Jaromír Dušek, Michal Dohnal and Jana Votrubová examined how water travels through structured soils. Their 2010 study used oxygen-18 as a natural tracer in precipitation, soil water and hillslope discharge. A dual-continuum model represented relatively slow movement through the soil matrix and faster movement along preferential pathways, with exchange between them. The isotope signal helped to examine the mixing of recent rainfall with water already stored in the hillslope. A rapid rise in discharge could thereby be investigated through its internal sources and pathways.

Additional observations also changed how models could be evaluated. In a 2012 uncertainty analysis, Dohnal and colleagues examined the sensitivity of a dual-continuum model and found that including oxygen-18 information improved the identification of parameters governing preferential flow. The result illustrates a broader methodological development. Agreement with river discharge alone can leave several possible explanations of internal catchment behaviour. A tracer measurement supplies another constraint, narrowing the set of explanations compatible with the evidence. Progress in computing and progress in observation

were therefore closely connected: increasingly elaborate representations needed measurements capable of testing the processes they described.

At the catchment scale, the BILAN model provided an enduring Czech framework for water-balance research. Developed at the Water Research Institute from the early 1990s, it represented storage and transfers of water through a conceptual description of the catchment. Daily and monthly versions served different analytical purposes. Its relatively modest computational requirements made it suitable for repeated calculations across many catchments and alternative scenarios. The approach supported a continuing interest in how precipitation is partitioned between evapotranspiration, changes in storage and runoff. Maintaining this balance remained essential when the questions shifted from present water resources towards possible future climatic conditions.

The development of ensembles made those future conditions more explicit as a source of uncertainty. A 2012 assessment by Martin Hanel, Adam Vizina, Petr Máca and Jiří Pavlásek applied BILAN to 250 Czech catchments, using scenarios derived from 15 regional climate simulations. The scenarios differed considerably in the size of projected runoff changes, although common seasonal tendencies could be identified. For the history of Czech hydrology, the important development was the comparison of alternatives within a consistent analytical framework. A future runoff regime could be discussed in terms of agreement, divergence and assumptions, giving a more informative account than a single projected value.

Observed low flows required equally careful attention to regional differences. Theodor Fiala, Taha Ouarda and Josef Hladný's 2010 investigation examined 144 Czech river basins over 1961–2005. Most stations showed no statistically significant trend in the variables considered. Among significant results, however, the researchers identified combinations including decreasing summer low flows, increasing winter low flows and longer drought duration. The distinction matters when describing scientific development after 1993. Concern about future drying was accompanied by attempts to establish precisely where, when and in which measures change could already be detected. National conclusions had to retain the unevenness apparent in the observational evidence.

The droughts of 2015 and 2018 intensified interest in hydrological deficits and their persistence. A 2021 study by Radovan Tyl, Václav David and Adam Beran compared precipitation, runoff and evapotranspiration in selected Czech catchments during 2015–2019. The lowest runoff occurred in 2018 across the catchments examined, although the year with the lowest precipitation differed between them. This distinction made the choice of hydrological evidence consequential: a ranking based on rainfall could differ from one based on river flow. The study also drew attention to reservoir operations and other interventions, whose effects had to be understood when interpreting an observed water balance.

Longer perspectives helped to clarify the interpretation of exceptional events. Hanel and an international team's 2018 reconstruction examined European droughts over approximately 250 years, considering precipitation, soil moisture and runoff. It showed that the apparent rarity of recent droughts depended partly on the variable, period and geographical extent being assessed. This contribution from researchers associated with the Czech University of Life

Sciences and cooperating institutions placed Czech expertise within a broader European enquiry. It also offered a useful discipline for national research: the severity of a drought cannot be established adequately through one indicator or through comparison with a short recent period alone.

Snow research brought another dimension into the analysis of summer water availability. Michal Jeníček and Ondřej Ledvinka's 2020 study modelled 59 mountain catchments, evaluating the calculations against observed runoff and snow water equivalent. Snow-poor years generally produced lower groundwater recharge, with consequences for summer baseflow. The research helped to explain why conditions during a dry summer may partly reflect the previous winter's snowpack. In a country with important mountain source areas, this connected seasonal snow studies with questions of water supply and drought. It also showed the value of testing a model against more than one observed component of the water cycle.

The interface with hydrogeology became particularly important when water resources were assessed over longer periods. The Czech Geological Survey's groundwater reassessment project of 2010–2016 examined 58 hydrogeological regions, combining geological interpretation with hydrological and groundwater-flow models. More than a hundred monitoring boreholes were drilled during the project. Its relevance to hydrological development lies in the connection between catchment water balance and the behaviour of aquifers. Surface observations, recharge estimates and subsurface structure had to be reconciled before the availability of groundwater could be interpreted. The work also linked the production of research evidence with the expansion of observational capacity.

Operational drought assessment further encouraged the combination of methods. The HAMR system, described by Vizina, Hanel, Miroslav Trnka and Daňhelka in 2020, brought meteorological, agricultural and hydrological information into a common presentation, while also addressing water availability and use. Its components included SoilClim, BILAN and WATERES, together with groundwater observations. The underlying distinction between drought and water scarcity was scientifically important: an unusual natural deficit and the inability of a resource to satisfy demand are related questions with different explanatory requirements. Such systems created a setting in which research on physical processes could be interpreted alongside information about the demands placed on water resources.

Flood research meanwhile extended towards short-lived events in small catchments. A 2021 study by Petr Novák and colleagues described the use of weather-radar information in the Czech Flash Flood Indicator. The system combined estimates and forecasts of rainfall with current soil saturation and the physical characteristics of the area. Experimental operation began in 2010, followed by recalibration and evaluation; by 2020 it had become an important part of the national forecasting system. This development illustrates the value of connecting atmospheric observation with hydrological state. The consequences of an intense shower depend on where it falls and on how much water the receiving landscape can still accommodate.

Continuing software development also altered how established methods could be used and examined. Petr Pavlík and Vizina's 2022 account of BILAN documented revised evapotranspiration options, a wider choice of calibration criteria and interfaces for working with the model. The evolution towards accessible source code and an R interface made the calculation easier to incorporate into repeatable research workflows. These changes were scientifically relevant because evapotranspiration estimates and calibration choices affect the remaining components of a simulated water balance. Methodological renewal could therefore involve revising a long-used model and making its assumptions easier to inspect, rather than replacing it with an entirely new system.

Repeated surveys from uncrewed aerial vehicles opened further opportunities for observing rivers and evaluating interventions. Langhammer, Theodora Lendzioch and Jakub Šolc's 2023 study followed three restored streams in Prague over six years. Photogrammetric reconstruction was combined with hydromorphological assessment to examine channel form, vegetation and features affecting restoration performance. The repeated observations revealed differences between planned and realised channel geometry, together with problems that limited restoration quality. For hydrology, the methodological value lay in observing development through time. The completion of construction marked the beginning of a measurable environmental response whose course still required explanation.

By 2025, the development of field instruments also included attempts to make dense observation less expensive and more reproducible. A Czech–German collaboration led by Veethahavya Kootanoor Sheshadrivasan published the picoSMMS soil-moisture monitoring system, with openly available hardware and software information. The study combined laboratory calibration with initial field deployments, including the Rokytka catchment in the Šumava Mountains. Early deployments exposed technical failures and prompted design revisions, an important qualification to claims about inexpensive monitoring. The contribution illustrates an expanding methodological frontier while preserving a familiar hydrological requirement: the behaviour of an instrument must be understood before its readings can be treated as dependable evidence.

Recent events kept the practical questions open. The Hydrometeorological Institute's assessment published in November 2025 identified the September 2024 floods as the year's principal flood episode, with estimated return periods of at least a century at 40 gauging profiles. The same assessment examined minimum flows, groundwater conditions and water quality. Its breadth illustrates the continued need to place a major event within the annual and regional behaviour of the water cycle. Increased research capacity enabled more detailed assessment, while the range of conditions requiring observation remained substantial.

A distinct methodological milestone came with the standard public presentation of probabilistic hydrological forecasts from mid-October 2025. The institute described forecasts based on 17 hydrological scenarios driven by ALADIN-LAEF meteorological forecasts over a 66-hour horizon. Presenting a range of possible future water levels and discharges made part of the uncertainty visible to forecast users. This was the operational expression of questions that Czech hydrologists had been investigating for decades. Across 1993–2025, the field had strengthened the connection between measured records, experimental explanation and

predictive calculation. Its continuing scientific task was to make those connections testable while keeping the assumptions and limits of each method clear.

Catchment Hydrology: Precipitation–Runoff Relationships, Snow Processes and Changes in Water Storage

A mountain stream may rise within hours of a downpour and continue to flow through weeks of fine weather. The two responses draw on water held in the same catchment, though on very different timescales. A brief rise can depend on how wet the slopes were before the rain arrived, while the flow in August may owe something to snow that melted in March. These relationships give the history of Czech catchment hydrology after 1993 its particular coherence. Investigations that began with the close observation of soils and streams came to encompass the seasonal movement of water through mountain ranges and the changing balance of precipitation, evaporation and runoff across the country. At each scale, the interpretation of discharge has depended on evidence about where water could accumulate and how long it was likely to remain there.

A catchment water balance makes the problem tractable. Over a specified interval, precipitation supplies water, evapotranspiration returns it to the atmosphere, and streamflow carries part of it past the outlet. The balance also allows for transfers across the boundary, including groundwater movement where the underground divide differs from the one traced on a map. Expressing the terms as depths of water over the catchment area makes a rain-gauge record and a river discharge series comparable. The change in storage then refers to the combined gain or loss from snow, soil, groundwater and other reservoirs within that boundary. The interval matters. A modest annual change can conceal a substantial winter accumulation followed by spring release and summer depletion.

The Volyňka basin provided a foundation for studying these exchanges long before the Czech Republic was established. In 1975 the Institute of Hydrodynamics set up the paired headwater catchments of Liz and Albrechtce in the Šumava region, where subsequent work could draw on measurements begun under Czechoslovakia. The records combined weather observations with measurements of soil moisture and the suction with which soil retains water. A study published in 1994 used meteorological observations to estimate plant transpiration from the energy available for evaporation when soil moisture was sufficient. The Liz synthesis of 2006 brought this line of enquiry back to the catchment. It examined how water retained in the soil and subsequently taken up by vegetation influenced the partition of precipitation between atmospheric loss and drainage.

Even the input to a forested water balance could prove elusive. In 1995 a study of the Šumava and Germany’s Taunus mountains examined the water deposited when cloud and fog droplets strike the canopy. The droplets are carried by the wind and may collect on needles and branches even when a conventional gauge records little rainfall. Some of the intercepted water evaporates, and some reaches the ground. For the Šumava setting examined in that study,

modelling put the net annual contribution at about 47 millimetres. The figure belonged to the site and assumptions used in the calculation. Its wider significance lay in identifying a measurable source of water whose importance depends on exposure, cloud conditions and the structure of the forest.

Long records also made it possible to ask whether forest change could be discerned in the runoff record. A 2009 comparison of forested experimental catchments used simulations to examine the divergence between calculated and observed flows over periods of changing vegetation. Agreement with recorded discharge gave a basis for comparing periods, while persistent departures prompted questions about water use by the forest. Such a departure can arise from uncertain rainfall measurements or from the way a model represents evaporation. Evidence about the history of the stand therefore matters alongside the hydrograph. The approach linked questions about forest condition to the water balance while keeping the various explanations open to investigation.

In the Jizera Mountains, the Uhlířská headwater catchment offered a way to follow water below the ground. Much of its sloping terrain has shallow, permeable soils over granite, and the valley floor contains sediments and wet organic soils. By the late 2000s, researchers were comparing stable isotopes in water with measurements of dissolved silica in rainfall, subsurface water and streamflow. The isotope composition of a storm can differ from that of water already in the catchment, while silica concentrations reflect contact with mineral material. Together the two measurements help to establish which stores contribute to discharge. A sharp rise at the outlet can result partly from water displaced from the soil or shallow subsurface as the storm alters hydraulic conditions upslope.

The connection between a hillslope and its stream can strengthen abruptly as the soil wets up. A 2016 modelling study examined how preferential stormflow, the rapid movement of water along relatively permeable routes, depended on both rainfall amount and the water already stored on the slope. The simulated threshold shifted with the distribution of moisture before the storm and with the timing of rain during it. Discharge could also differ at the same estimated level of hillslope storage on the rising and falling sides of the event. The routes that had become connected during wetting drained in a different sequence as the storm ended. A rainfall total was therefore more informative when accompanied by observations of antecedent moisture and the course of the storm itself.

In the upper Vydra basin of the Šumava, the record from 1961 to 2010 allowed changes in seasonal runoff to be examined in a landscape affected by windstorms, bark beetle damage, forest management and warming. The study, published in 2015, found that the overall runoff balance remained broadly stable while the timing and composition of streamflow changed. Seasonal discharge and the proportions attributed to faster and slower components showed changes that an annual total could obscure. Because the changes in climate and forest condition overlapped in time, the record supported an interpretation of their combined influence more readily than an exact division between them. It also illustrated why a catchment can deliver a similar quantity of water over a year under a different seasonal regime.

Snow adds a reservoir whose dimensions are visible but whose water content has to be measured. Snow water equivalent expresses the depth of liquid water that a snowpack would yield if it melted. Two snowpacks of equal depth can therefore represent different water stores if one has compacted or become wetter. A field survey combines measurements of depth and density at sampled locations, then uses the distribution of terrain and vegetation to infer conditions between them. Elevation affects the probability that precipitation falls as snow and the duration of the pack. Wind exposure, shade and the position of the canopy determine how much of that potential store accumulates at a particular site and when it begins to drain.

Measurements published in 2014 from a forested mountain catchment compared snow under spruce and beech with snow in the open at elevations between roughly 835 and 1,118 metres. Across the sites examined, the water equivalent of snow on the forest floor was, on average, about half that in the open. The elevation gradient in accumulation was also weaker under the canopy. Intercepted snowfall may be unloaded later, melt and drip, or sublime directly into the air. During the melt season the same canopy can shelter the snow below from solar radiation. Forest cover thus has effects at two stages, and a spring survey needs to be read in light of both the preceding accumulation and the melt already under way.

A study published in 2018 connected snow surveys with hemispherical photographs taken beneath the canopy. The photographs helped characterise the density and geometry of the overhead foliage. Canopy structure was especially informative about the amount of snow that had accumulated, while the distribution of incoming radiation helped explain differences in the rate of loss during melt. Clearings tended to accumulate a larger store, and their greater exposure could hasten its release. The investigators could therefore distinguish areas that held a large amount of water at the end of winter from areas likely to retain snow longest. These spatial differences matter when a catchment estimate is derived from observations at a handful of accessible points.

Where a river crosses a national boundary, estimating the winter store also depends on observations made upstream in another country. A Polish account of the Oder basin published in 2021 describes how the Polish and Czech hydrometeorological institutes exchanged snow data, made field measurements to assess the water held in the snowpack, and worked on hydrological modelling in the basin. Their cooperation also included simultaneous discharge measurements on boundary rivers. Joint measurements helped the two services resolve differences in the discharge estimates they used to interpret the response of these rivers.

Extending the analysis back through several decades required a different strategy. A reconstruction published in 2021 used a snow model to estimate seasonal snowpack in 40 catchments across five Czech mountain regions from 1965 to 2014. The strongest declines occurred in the western part of the study area, and some catchments showed snow seasons shortening by as much as 6.8 days per decade, chiefly through earlier melt-out. The relative influence of temperature and precipitation varied with elevation. Temperature had greater explanatory power at lower elevations, where winter conditions more often approach the freezing point. At higher elevations, where cold conditions permit snowfall to persist, changes in the amount of precipitation played a larger role. The results give a geographical meaning to a trend that would look much simpler in a countrywide average.

The significance of the winter store for river flow was quantified in a 2020 analysis of 59 Czech mountain catchments. A model evaluated against daily discharge and snow water equivalent was used to follow water originating as snow through the simulated catchment. Snowfall accounted for about one fifth of precipitation on average, while snowmelt contributed about one quarter of annual runoff. During the cool season and the early part of spring, atmospheric demand for water is generally lower than in summer. Water released during this period can pass into the drainage system or replenish the subsurface before vegetation reaches its greatest demand. The estimated share of snowmelt in runoff consequently depends on the time of release as well as the quantity stored in winter.

The same analysis showed how this influence could persist after the snow had disappeared. Low-snow winters tended to produce earlier melt and smaller modelled groundwater recharge. The lowest summer baseflow generally occurred when a winter with little snow was followed by a dry summer. Summer rainfall and evapotranspiration still shape the severity of the low flow, and the winter contribution varies among catchments with different storage and drainage properties. The distinction between origin and route is especially important here. Water assigned a snow origin by the model may have reached the stream over the course of the melt event or remained underground and entered it weeks or months later.

Climate projections extended the enquiry from observed variability to possible changes in the seasonal balance. In a 2021 study of Czech mountain catchments, the simulated maximum snow water equivalent declined by about 30 to 70 per cent by the end of the century across the scenarios examined. Melt occurred, on average, some three to four weeks earlier, with implications for the timing of runoff and the water available in spring. An increase in winter precipitation could partly compensate for the loss of snow, depending on where the additional water went and how quickly it drained. These projections concern a redistribution through the year. Even where winter flow increases, a smaller snow reservoir can leave less water available at the time when soils and aquifers would ordinarily receive their spring replenishment.

Rain falling on snow brings this seasonal reservoir into the analysis of individual storms. A cold pack can retain some incoming water or refreeze it, while a wet snowpack may transmit liquid rapidly and supply additional meltwater. The amount reaching the stream also depends on the conditions below the snow. A 2021 Central European investigation found that many rain-on-snow events produced modest runoff and that rainfall amount was an important determinant of the larger responses. Many of the high-runoff cases occurred early in winter. The study gave a more discriminating account of a category often identified simply from the concurrence of rain and snow. A hydrological assessment also has to establish the condition of the pack and the state of the catchment when the rain arrives.

In 2025 a modelling comparison of 93 mountainous catchments, including 60 in Czechia, explored how rain-on-snow might change under combinations of warmer temperatures and altered precipitation. In the warmest experiments, the number of such days declined by about three quarters in the Czech sample. This reflects the dwindling opportunity for rain to fall on an existing snowpack as snow cover becomes less persistent. The seasonal response could differ from the annual one. In some experiments with higher precipitation, the contribution to runoff from these events increased during winter even as the annual share fell. Comparing Czech

catchments with German and Swiss examples helped to relate those outcomes to their different elevation ranges and to the temperatures at which snow is normally retained.

Once meltwater reaches the ground, its further history can be much longer than that of the snowpack. At Uhlířská, a study published in 2017 sampled groundwater from three boreholes and used several tracers to estimate recharge and apparent water ages. Hydrogen and oxygen isotopes helped characterise recharge, while dissolved gases, including chlorofluorocarbons, offered information about the time since water entered the subsurface. The estimated ages spanned years to decades and differed with depth and tracer. Mixing between waters of different ages makes such figures characteristic of the sample and its interpretation. A catchment capable of producing a fast rise in streamflow can thus also contain groundwater whose passage through the subsurface extends well beyond the season in which it was replenished.

Peatland studies brought the question of available storage into view. A German–Czech project reported in 2013 compared headwater basins in the Ore Mountains and the Šumava with different proportions of peat and peaty soils. The variation in their runoff responses raised questions about when a bog could hold back water. In the Rokytka catchment of the Šumava, research published in 2021 paired observations of the peat water table and mineral soil moisture with streamflow measurements and modelling. The model assigned a greater role to rapid runoff from the peat and to slower drainage from slopes with Podzol soils. During wetter periods the peat areas contributed more runoff. A bog can hold a great deal of water and have little capacity to absorb additional rainfall when its water table is near the surface.

The water stored in a peatland is also distributed unevenly over short distances. At a montane site investigated with drone-borne multispectral and thermal instruments, a study published in 2024 documented a substantial contraction in shallow waterlogged areas during drought. The imagery revealed where wet surfaces persisted and where the pattern fragmented as conditions became drier. Surface temperature and spectral reflectance helped to map those changes over areas that would have been difficult to sample densely on foot. Water-table and soil measurements supply the corresponding information below ground. Estimating the volume of water lost also requires information on the thickness and porosity of the layers that dried.

At catchment scale, changes in the capacity of soils to hold plant-available water can have different consequences for crops and streams. A 2022 modelling study examined hypothetical increases in this capacity across 133 Czech catchments. Extra retention could reduce agricultural drought by sustaining water uptake through dry periods. Some of that water would subsequently return to the atmosphere through transpiration, with less left to recharge aquifers or sustain flow downstream. The simulations showed a potential intensification of hydrological drought in some settings, particularly where the climatic water balance was already unfavourable. The outcome depended on the climate and catchment assumptions. The study made explicit the need to distinguish the maximum accessible store in the rooting zone from the amount of water that subsequently leaves it as drainage.

The droughts of 2018 and 2019 put changes in storage into a wider Central European setting. Measurements from the GRACE Follow-On satellites used changes in the gravity field to estimate anomalies in the total mass of water on and beneath the land. The regional analysis found a larger storage deficit in 2019 than in 2018. A satellite estimate of this kind integrates several reservoirs over a broad footprint. Soil measurements, groundwater levels and snow observations are needed to determine which stores account for changes within a particular catchment. The regional record provides a complementary view of whether depletion extends across the surrounding landscape and persists from one season to the next.

A national study published in 2024 compared estimates of precipitation, evapotranspiration and runoff across six decades. The investigators assembled combinations of datasets and examined how closely their water budgets closed. The most robust annual change was an increase in evapotranspiration, while the strength and direction of some other changes depended on the season, region and data used. Differences between estimated fluxes arise partly from the way each product represents the land surface and partly from the uncertainty of the input observations. Assigning a residual to snow, soil moisture or groundwater therefore requires independent information on those stores. The comparison located the changes that could be detected consistently and the scales at which the estimates diverged.

By the end of 2025, the CAMELS-CZ dataset made daily discharge, meteorological series and standardised catchment attributes available together for large-sample studies. A researcher could use common variables to compare the response to a dry winter across many river basins, or to examine whether the influence of antecedent wetness differed between areas with different soils and topography. Such comparisons bring the hypotheses developed at Liz, Uhlířská and the Šumava peatland sites into contact with a much wider range of conditions. The field sites retain their importance because they supply measurements of the processes that discharge alone leaves unresolved. The value of a larger sample is that it allows the extent of each explanation to be tested across catchments with different climates, vegetation and capacities to retain water.

Floods and Hydrological Drought: Research, Forecasting and the Assessment of Water-Related Risks

Czech rivers supplied some of the most demanding tests of the country’s environmental science between 1993 and 2025. The floods of 1997 and 2002 exposed weaknesses in observation, forecasting and the protection of settled floodplains. The prolonged dry years of the following decades brought a different set of questions about the persistence of low flows and the capacity of water supplies to withstand repeated seasons of poor replenishment. Research developed through the investigation of particular events, the analysis of long records and the testing of models against observations. An estimate of how high a river might rise, or how long its flow might remain depleted, increasingly formed part of a wider assessment of the people, infrastructure and ecosystems affected.

The distinction between a forecast and a frequency estimate runs through this history. A forecast describes a possible development over the coming hours, days or weeks, starting from the conditions observed at the time of issue. A frequency estimate concerns the likelihood of events of a given magnitude over many years. During the 1990s Šárka Blažková and Keith Beven developed the latter approach for Czech catchments with limited observations. Their 1997 study coupled a stochastic rainfall generator with TOPMODEL, allowing simulated storms and catchment responses to produce a distribution of flood peaks. It opened a way to investigate rare floods while examining the influence of uncertain model parameters and the limited length of the observed record.

The July 1997 disaster gave these questions immediate public importance. Prolonged rainfall over the northern mountains produced severe flooding in the Oder and Morava basins, with damaging interactions between waves arriving from different tributaries. The subsequent government assessment assembled evidence from the hydrometeorological service, river authorities and the organisations responsible for emergency response. It identified the need for more timely information in areas where rivers respond quickly to rainfall. Measures reported in 1998 included additional routes for transmitting observations and warnings, together with public access to radar information and flood reporting through television teletext. These developments connected the scientific problem of observing a fast-changing catchment with the practical problem of delivering its interpretation to the authorities and residents downstream.

In August 2002 the sequence of rainfall itself became central to understanding the disaster. Two major episodes, on 6–7 and 11–13 August, affected the Elbe basin within a short interval. The first increased catchment wetness and filled some of the available reservoir space before the second arrived. Flood waves from the Vltava and other tributaries then propagated through a river system extending into Germany. The International Commission for the Protection of the Elbe documented the event in a German-language synthesis published in 2004. Its account brought the rainfall and river records from the two countries into a common analysis. The findings also showed how reservoir operation and floodplain storage changed the shape and timing of the wave as it travelled downstream.

The observation system available during the June 2013 floods reflected substantial investment since 1997. Automatic stations supplied water levels and rainfall much more frequently, and internet services carried observations and forecasts to a wider audience. Local warning networks expanded particularly after the flash floods of 2009, supplementing the national network on smaller streams. The 2014 synthesis edited by Jan Daňhelka, Jan Kubát, Petr Šercl and Radek Čekal placed these developments alongside the evaluation of the 2013 event. By then, the AquaLog and HYDROG systems had accumulated more than a decade of operational experience. Maintaining the observations, updating model states and interpreting successive weather forecasts had become recurring activities through which research methods could be tested during actual floods.

An archive of issued forecasts made the performance of the whole forecasting process accessible to scrutiny. Tomáš Vlasák and Jan Daňhelka’s 2010 assessment examined AquaLog forecasts for the Elbe basin during 2002–2008. It considered the forecast hydrographs and the

successful or unsuccessful prediction of flood-stage exceedances. Distinguishing hits, missed events and false alarms made the results relevant to the decisions taken by forecast users. Performance varied between locations and generally deteriorated with increasing lead time. A useful evaluation therefore had to retain information about the river, the severity of the event and the interval between issue and predicted occurrence. A single score averaged across ordinary flows and floods would give a much less precise account of that performance.

Forecast lead time has a particular geographical significance in Czechia. Much of the river network lies close to its headwaters, where the time available to observe rainfall and wait for the resulting water to arrive can be short. Lucie Březková and colleagues examined this problem in a 2007 study of flood predictability, including cases from the Dyje basin. A displacement of the predicted rainfall maximum can move the heaviest rain into a neighbouring catchment and substantially alter the calculated flood. Increasing the spatial detail of the hydrological model leaves that uncertainty in the atmospheric input to be addressed. Comparing plausible rainfall developments gives forecasters a way to assess how sensitive the river forecast is to the location and timing of the storm.

Radar offered a means of following intense rainfall between gauges and at intervals relevant to rapid runoff. Milan Šálek, Lucie Březková and Petr Novák used the HYDROG model to investigate flash floods that occurred in 2002 and 2003. Their 2006 paper combined ten-minute radar estimates with short forecasts obtained by extrapolating the movement of radar echoes. The simulated forecasts lagged behind the actual development, reflecting the difficulty of predicting the growth and decay of convective storms. Even so, the experiments identified an opportunity to warn places reached later by the flood. The value of a short rainfall forecast depended on where it entered the drainage network and on the remaining travel time to a threatened settlement.

By 2021, work led by Petr Novák had made the correction of radar rainfall an explicit component of flash-flood assessment. The MERGE2 method combined radar estimates with rain-gauge measurements using geostatistical interpolation. An adjustment coefficient could also be applied when the corresponding gauge observation had yet to become available. Testing the procedure on intense-rainfall cases addressed a practical difficulty in real-time forecasting. The most spatially extensive observation arrives quickly, while the measurements used to correct its bias may arrive later. The development of the rainfall product consequently affected both the estimated amount of water entering a catchment and the speed with which its runoff response could be assessed.

The Flash Flood Indicator brought these observations into a system covering small catchments across the country. The 2023 account by Petr Šercl and his colleagues described calculations based on estimated antecedent soil wetness, catchment characteristics and recent or forecast rainfall. The system represented connected river reaches so that danger could be assessed downstream of the area receiving the storm. A separate calculation addressed local inundation within individual grid cells. This made a useful geographical distinction between water accumulating near where the rain fell and a flood wave advancing through the stream network. For locations with sparse streamflow observations, the calculations supplied a

relative indication of a developing threat that could be interpreted alongside radar and local reports.

Flood-risk mapping developed in parallel with these operational methods. In 2010 Aleš Dráb and Jaromír Říha at Brno University of Technology described procedures being developed for Czech implementation of the European Floods Directive. Their approach combined information on inundation probability and intensity with the uses of the exposed land. Water depth and flow velocity helped characterise the physical danger, while cadastral and building information supported the assessment of consequences. The resulting maps made it possible to compare places flooded to a similar depth but occupied by different activities. They also allowed the residual danger associated with events exceeding the protection provided by a defence to enter the assessment, alongside the conditions under which the defence was expected to operate.

The consequences of a flood also depend on what households can afford, understand and undertake. A 2015 study led by Robert Stojanov examined adaptation in a rural part of the Bečva basin using a questionnaire survey addressing 605 households. The analysis associated protective action with previous flood experience, the damage sustained and perceptions of future danger. Education and household composition also influenced the measures reported. These findings brought social geography into contact with hydrological risk assessment. A map could establish which homes were exposed, while household research could examine why some residents acted on that information and others adopted fewer measures. Interpreting the uneven consequences of repeated floods required both kinds of evidence.

Questions about very rare floods continued to demand methods that could make use of several forms of observation. In 2009 Blažková and Beven applied a limits-of-acceptability approach to the Skalka catchment on the Ohře, whose headwaters extend across the Czech–German boundary. Simulated rainfall, snow water equivalent and discharge were compared with predefined acceptable ranges. Early rejection of all candidate models prompted changes to the representations of rainfall and runoff. Retained simulations were then used to estimate extreme peaks relevant to dam safety. The investigation exposed the influence of both observational error and the chance properties of a short record. Its estimates of rare-event discharge were accompanied by a range reflecting the models that remained consistent with the available evidence.

Low-flow research faced a related difficulty in drawing conclusions from highly variable records. Theodor Fiala, Taha Ouarda and Josef Hladný analysed 144 Czech river basins for 1961–2005 in a study published in 2010. They distinguished mountain and lowland regimes and examined seasonal seven-day minima, the duration of flow below selected thresholds and the associated deficit volumes. Statistically significant changes occurred at a minority of stations. Among the detectable patterns were declining summer low flows and increasing winter low flows, with longer and larger deficits in parts of the north-east. Their geographical distribution helped identify where particular forms of drought vulnerability might be emerging. The results also showed why conclusions depended on the season and on the measure chosen to describe low flow.

The volume of a deficit gives a prolonged low-flow episode a dimension that its minimum discharge alone cannot convey. It accumulates the shortfall below a specified threshold over the duration of the event. Filip Strnad and colleagues used this principle in a 2017 regionalisation of drought characteristics for 133 Czech catchments. Their calculations used BILAN simulations driven by a long meteorological series and defined deficits relative to the lower twentieth percentile of monthly flows. Catchments were grouped using climatic and hydrological characteristics, with hydrogeology also informing the classification. Regional frequency analysis then allowed information to be shared among basins with similar behaviour. The method linked the severity of an individual drought to estimates of how often comparable shortages might arise.

Longer reconstructions changed the temporal context of such assessments. Martin Hanel and a Czech–German research team examined European droughts over 1766–2015 in a study published in 2018. Reconstructed meteorological conditions drove hydrological simulations that distinguished precipitation deficits, runoff and soil moisture. The ranking of recent droughts depended on which component was considered and on their spatial extent. Earlier severe events provided a broader comparison for the widely discussed droughts of 2003 and 2015. The reconstruction extended the evidence available to Czech hydrologists beyond the period of dense instrumental monitoring. It also made the propagation of a meteorological deficit through the water cycle part of the explanation of an event’s severity.

The preliminary Czech assessment of the 2018 drought, edited by Daňhelka and Kubát and published in 2019, documented the consequences of several successive dry years. In some areas, groundwater had already remained depleted through earlier seasons, so low river flows and low groundwater levels accompanied the new meteorological deficit from an early stage. The report was still describing continuing groundwater drought as it was prepared. Recovery therefore had to be assessed separately in the different parts of the water cycle. Rain could wet the upper soil and improve conditions for vegetation while deeper stores remained depleted. The sequence of dry years gave water-resource research an opportunity to examine accumulated depletion and the different timescales over which rainfall could restore flow and groundwater levels.

Resource assessment added the distribution of water use to this hydrological description. A 2017 study by Adam Vizina and colleagues evaluated the water balance of 133 Czech intercatchments and coupled it with a simplified representation of water-resource management. BILAN supplied information about the hydrological fluxes and stores, while the WATERES calculations examined available resources under different drought conditions. The comparison distinguished the water generated within an area from the resources available after flows through the wider river system and human uses had been considered. It gave the assessment of hydrological drought a direct connection to supply reliability. A similar natural shortfall could have different consequences in areas served by different combinations of reservoirs, abstractions and transfers.

Long-term planning also drew on climate scenarios. A 2012 study by Hanel, Vizina, Petr Máca and Jiří Pavlásek applied BILAN to 250 Czech catchments using changes derived from 15 regional climate simulations. The comparison concerned mean runoff in 2070–2099 relative to

1961–1990. Although the estimated magnitudes varied, the scenarios commonly indicated declining spring and summer runoff across much of the country. Increases in winter flow were more prominent in northern, higher catchments. The analysis gave planners a way to examine seasonal pressures on resources under several possible climates. Its runoff projections concerned changes in seasonal means, with further analysis required to estimate the frequency of particular drought events.

The HAMR system gave drought assessment a public and operational form. The account published in 2020 by Vizina, Hanel, Miroslav Trnka and Daňhelka described weekly indicators combining meteorological and agricultural conditions with surface-water and groundwater status. SoilClim, BILAN and WATERES supplied different components. Simulated runoff supported the surface-water assessment, while shallow-aquifer observations informed the groundwater component. Their joint display helped users follow where deficits persisted. The collaboration linked the T. G. Masaryk Water Research Institute, CzechGlobe, the Czech University of Life Sciences and the hydrometeorological service.

The 2020 description also presented short-range forecasts based on several weather models and a statistical outlook extending to eight weeks. These products helped users assess the prospect of improvement during a dry episode. Their interpretation depended on the store being assessed. Rain could improve surface conditions before enough water reached an aquifer to reverse its depletion.

Ecological research supplied another way to recognise drought impacts in small streams with limited hydrometric records. Michal Straka and an international team developed the Biodrought index, published in 2019, from benthic macroinvertebrate communities sampled in streams with different patterns of flow permanence. Organisms differ in their ability to survive drying or recolonise after water returns, so the composition of a community can retain evidence of a previous dry phase. The index used that response to estimate the probability of recent stream drying. It extended assessment to locations where a gauging station was absent and a brief visit after rainfall might find water flowing again. The collaboration connected Czech hydrology and freshwater ecology with research in Britain and France.

September 2024 brought the two extremes into the same event sequence. Many rivers were at low-flow or drought levels before prolonged rainfall associated with the low-pressure system Boris arrived. The initially dry landscape absorbed water, after which continued rain drove rapid increases in runoff. The 2025 evaluation by Šercl, Vojtěch Svoboda and Miloň Boháč examined this progression alongside tributary waves and reservoir operation. Advance rainfall forecasts allowed managers to create additional reservoir space. At Vranov and several reservoirs in Moravia and Silesia, observations documented attenuation of the flood wave.

Measuring the extreme flows also required reconstruction. The 2025 evaluation described destroyed gauges and extensive channel changes. The relation between water level and discharge had to be reassessed where channel geometry had changed or flows exceeded the range of direct measurements. Flood marks and hydraulic calculations helped establish peak estimates for reviewing flood-frequency values.

The assessment published one year after the flood also returned to the interpretation of forecasts. The Ostrava branch of the hydrometeorological service reported the need for wider presentation of probabilistic forecasts, more forecast locations and better explanation of predictive uncertainty to professional and public users. Such products already had precedents in earlier Czech forecasting work. The 2025 findings concerned their further application and communication during a high-consequence event. They placed particular importance on the information accompanying a forecast, including its issue time, range of plausible outcomes and dependence on the rainfall prediction. The same review showed the damaged Raškov gauge on the Morava alongside the provisional installation put into service in December 2024. Restoring the record was itself part of the work needed to evaluate the flood and prepare the next forecast.

Hydrogeology and Groundwater Research: Aquifers, Water Resources and Environmental Pressures

A well beside the Jizera draws on a different history of water from a spring rising through the granite at Karlovy Vary. In the river valley, the passage of water through gravels can depend on the level of the river and on nearby pumping. In the granite, a small number of connected openings can convey water to the surface from considerable depth. Across the Czech Republic, such differences in the movement and renewal of groundwater have guided research since 1993. The period brought increasingly detailed maps of the country's aquifers, new ways to follow the origin and age of their water, and closer scrutiny of the effects of abstraction, drought and pollution. The connections between these enquiries are clearest where the same aquifer feeds public wells, springs and streams.

At the beginning of the period, a contribution by Jiří Krásný gave hydrogeologists a common basis for describing how readily aquifers transmit water. Transmissivity expresses the capacity of the saturated thickness of an aquifer to conduct flow under a hydraulic gradient. A thick formation with modest permeability can therefore transmit substantial quantities of water. Krásný's classification, published in 1993, recorded both the magnitude and the variability of transmissivity. The second property is particularly informative in formations where a productive borehole may be separated by a short distance from one that encounters few connected fractures. Expressing the distribution in a consistent way made results from local investigations easier to compare and represent on regional maps.

Regional accounts gave these measurements a geological setting. Ferdinand Herčík, Zdeněk Herrmann and Jaroslav Valečka published a Czech monograph on the Bohemian Cretaceous Basin in 1999, followed by an English-language synthesis in 2003. The latter described the units used to assess groundwater resources across the basin and included twelve map appendices. The basin's extent made such a synthesis particularly important. A borehole can establish the succession of beds at one point, while regional maps allow investigators to consider where the

same beds crop out and where they are covered or interrupted. The maps made the evidence from local exploration available for interpreting groundwater circulation across the basin.

The revision of Czech hydrogeological zoning in 2005 carried an older mapping tradition into a digital environment. The national schemes of 1965, 1973 and 1986 had provided units for exploration and resource assessment. As Miroslav Olmer explained in 2009, the revised geographical information system could represent three layers at a scale of 1 to 50,000. A shallow layer, the basal Cretaceous aquifer and a main layer could be examined separately where their extents overlapped. The scheme also brought hydrogeological districts into closer correspondence with the groundwater bodies used in European water reporting. A district boundary remained an interpretation of the geology and flow. Where a divide was inferred from water levels, a substantial change in abstraction could change the direction of flow across it.

Fractured rocks were already the subject of a substantial international exchange. The Prague conference of 2003 led to the volume edited by Krásný and John M. Sharp, Jr., published in 2007. It placed field observations, resource assessments and numerical models from hard-rock settings in a common discussion. Weathered material near the surface may hold water, while open fractures provide paths through the underlying rock. The relation between these features varies with depth, fracture continuity and the history of weathering. Studies at the scale of a borehole or tunnel could therefore inform regional assessments by showing where assumptions of uniform permeability would give an incomplete account of groundwater flow.

The Czech Geological Survey’s national synthesis of 2012 assembled more than four decades of regional surveys and mapping. Krásný and his co-authors considered ordinary groundwater and mineral waters within the same account of the country’s geology. Sedimentary basins could be read as sequences of permeable beds separated by formations that impede vertical flow. In much of the crystalline terrain, groundwater occurrence depended on the condition of the weathered zone and the distribution of open fractures. River valleys added shallow bodies of permeable sediment, and soluble limestones contained locally developed conduits. Presenting these settings in one work made it possible to relate the behaviour of individual springs and wellfields to wider geological patterns.

Resource reassessment gave that regional understanding a more directly quantitative application. Between 2010 and 2016 the Czech Geological Survey led the Rebilance project in 58 hydrogeological districts, selected for the importance of groundwater to their supplies. The work used 1981–2010 as the reference period for assessing long-term natural resources. Geological surveys and boreholes refined the description of aquifers, while hydrological models supported estimates of recharge and discharge. In sedimentary basins and Quaternary deposits, numerical flow models made it possible to represent groundwater levels and directions of flow. More than a hundred monitoring boreholes were drilled, with sites progressively incorporated into the national network run by the Czech Hydrometeorological Institute. The new observations allowed later assessments to return to the geological interpretations made during the project.

The 2016 report on the Liběchovka and Pšovka district showed what this meant for a particular water supply. The hydraulic model placed part of the recharge area of the Řepínský důl wellfield

in a neighbouring district and indicated that the Pšovka itself contributed water through infiltration. The assessment therefore considered the wellfield and its contributing area in detail. It used long records of pumping together with measurements and calculations of streamflow, including the need to leave a minimum flow in the Pšovka. The two valleys also contained groundwater-dependent wetlands. A model of recharge and drainage consequently became a way to examine the consequences of pumping in the streams and valley floors served by the same water.

Water sampled within a single formation can reflect very different routes through it. In 2010 Zdeňka Churáčková and colleagues reported on springs and boreholes in the eastern and north-eastern Bohemian Cretaceous Basin. Tracer evidence and nitrate concentrations distinguished relatively mobile water in preferential flow zones from water moving slowly through less active parts of the aquifers. Springs and heavily pumped wells were more likely to intercept the mobile component, which often contained more nitrate in the investigated settings. Some monitoring wells mainly sampled slower water. This distribution had a direct bearing on the design of a monitoring network. The location and screened interval of a borehole determine which part of the system supplies the sample and which contamination pathways the record can reveal.

By 2024, work led by Jakub Mareš was examining older groundwater in two districts of the same basin, on the right bank of the Jizera and in the Liběchovka and Pšovka area. Very low tritium activity helped identify water containing little recent recharge. The investigators sampled important supply installations and measured the yields of springs associated with that older component. Their first interpretation used lithology, groundwater levels and chemical measurements to propose an area of recharge around the quartz sandstones near Bezděz. They presented the inferred route as a model to be tested. Its resource significance depended on establishing where the water entered the aquifer, how it mixed with younger water and how much of it reached the points where it could be abstracted.

The Bedřichov water-supply tunnel in the Jizera Mountains offered access to groundwater entering an excavation through crystalline rock. Petr Rálek and Milan Hokr reported in 2013 on continuous measurements that followed five years of manual observations. Different instruments were needed for dripping water, more substantial individual inflows and the combined discharge in the tunnel’s collection channel. Dilution measurements helped locate changes in flow along the tunnel. The arrangement made it possible to examine both the distribution of water-bearing openings and the variation of inflow over time. It showed how the detail of field instrumentation could improve the description of a fractured formation that a conventional borehole samples only along its own narrow path.

Research on mineral and thermal waters extended the enquiry to the circulation feeding springs. At Karlovy Vary, a team led by David-Aaron Landa reported at the 2025 European Geosciences Union assembly on borehole imaging and tracer tests in the granite beneath the spa. The tests used access provided by boreholes drilled to investigate or collect thermal water. Some routes transmitted tracer rapidly towards the spring system, while an injection into strongly altered granite gave evidence of substantial storage and weak connection to the monitored outlets. The results were presented as field evidence for a heterogeneous network

of pathways. They brought the inherited problem of explaining the spa’s spring yields into contact with observations of individual fractures and conduits.

In limestone, solution can enlarge openings and alter the relation between a surface catchment and the water draining beneath it. A sinking stream may deliver water into a conduit with a short transit time. Rain entering the soil and small fissures can take longer to reach the same underground system. At the international karstological school in Postojna in 2004, Jiří Bruthans and colleagues reported a comparison of Czech karst springs using both tracer tests and environmental tracers. The two methods helped identify different parts of the same flow system. Rapidly connected pathways could coexist with water that had spent years or decades in the rock.

In the Moravian Karst, Jiří Kamas and colleagues used cave drips beneath fertilised land, forest and areas converted to grassland to investigate the passage of nitrate. Their 2015 study drew on sampling from several periods beginning in 1992. The response to changes in land use depended on the thickness and properties of the overlying rock. Beneath the thickest sections examined, about 105 to 120 metres, the estimated mean nitrate residence time exceeded 16 years. Such a delay affects the interpretation of observations made after a change in cultivation. The water sampled in a cave can still carry evidence of earlier land use, and the boundary of the contributing area needs to be inferred from flow through the rock as well as from the position of the drip.

The mapping of susceptibility to contamination brought some of these considerations together at national scale. In 2013 Pavel Novák and colleagues combined information on soils, the vulnerability of the rock environment and potential recharge to produce a synthesis map. Properties such as transmissivity and the character of groundwater circulation were incorporated in the geological layer. The resulting classes represented differences in the ease with which water and dissolved substances might reach an aquifer. Such an assessment describes the physical setting in which contamination could develop. To interpret a particular observation, it must be combined with knowledge of the substances released, the places where they enter the ground and the conditions that affect their transport.

In the alluvial gravels used by the Káraný waterworks, the movement of river water into an aquifer is part of the supply system itself. Bank filtration draws water through sediments adjoining the Jizera. The works also use artificial recharge to introduce river water into the aquifer through infiltration facilities. Zbyněk Hrkal and colleagues investigated pharmaceuticals and personal care products in this setting over two years, publishing their results in 2018. Their monthly sampling related the compounds detected in the river to the concentrations found along the two supply routes. Several substances were repeatedly detected in the artificial-recharge output, while the corresponding mixed bank-filtration sample had fewer consistent detections. The finding concerned the conditions at Káraný, where the paths and times available for attenuation differed between the two systems.

Long-term national observations set these local studies in a wider context. Groundwater levels in shallow and deep boreholes and the discharge of springs supply different evidence about the condition of an aquifer. A change of level can reflect variation in recharge, a change in

pumping or the transmission of pressure through a confined formation. The 2023 report on the environment, published in 2024, illustrated the value of retaining those distinctions. Shallow levels and spring yields were broadly normal over the year at national scale, with substantial regional variation. Deep groundwater levels remained below normal for much of the year, including persistent deficits in parts of the North Bohemian Cretaceous system. Taken together, the records showed that replenishment had progressed differently across the groundwater systems being monitored.

The 2024 hydrological yearbook, issued in 2025, assessed groundwater quality using samples from 725 monitoring sites. The programme covered basic chemistry, metals, pesticides and selected other organic substances, with different coverage for some groups of compounds. Nitrate remained a recurring source of elevated values, and pesticide transformation products featured among the frequently detected substances. Their presence illustrates the value of measuring compounds formed after application as well as the original chemicals. A long record also allows shifts in the chemistry of groundwater to be compared with changes in cultivation or land use. Interpretation depends on the sampling network and on the list of substances measured in each programme.

The legacy of uranium production posed a different problem in the northern Bohemian Cretaceous Basin. At Stráž pod Ralskem, chemical extraction introduced leaching solutions into the uranium-bearing Cenomanian formation. Conventional mining and dewatering at nearby Hamr also altered the regional hydraulic conditions. The geological evaluation published by Kopecký and Slezák in 2002 described the disposition of the exploited formation and the importance of protecting neighbouring groundwater used as a resource. Designing the restoration required a reconstruction of the history of injection and extraction, as well as of the connections between water-bearing layers. A contaminated aquifer had to be studied as a moving body of water whose flow field had itself been modified by mining.

In a 2002 study of remediation at Stráž, Hana Čermáková, Jan Novák and Jiří Mužák used the SATURN_2001 modelling system to examine extraction from the Turonian aquifer. The model represented reactive transport and accounted for the exchange between more mobile and less mobile parts of the formation. Field data were used to calibrate the model before a remediation variant was evaluated. Miroslav Jurda and Miloslav Němec’s 2022 account placed such work in the longer transition from uranium extraction to site restoration. The operational problem was to capture and treat contaminated groundwater while managing the hydraulic effects of the extraction. The need to observe how water chemistry and groundwater levels changed continued long after the end of production.

Cross-border studies showed why national records sometimes had to be read together. In the Intra-Sudetic Basin, the succession of water-bearing strata extends between the Czech Republic and Poland. A bilingual report published in 2014 documented coordinated monitoring in 2005–2012 around Police nad Metují and Kudowa-Zdrój, Krzeszów and Adršpach, and in the upper Ścinawka basin. Measurements were interpreted for the particular geological horizons intercepted at the observation sites. This made it possible to compare seasonal changes in equivalent formations across the border. The report also brought together geological

descriptions and discharge observations that had been collected by institutions with separate national responsibilities.

Along the Saxon border, the ResiBil project studied groundwater in the Cretaceous rocks of Děčínský Sněžník, the Hřensko–Kirnitzsch area and the Lusatian Mountains. The work ran from 2016 to 2020 in the account of Pavel Eckhardt and colleagues. The modelling domains were enlarged to represent the relevant flow systems more fully, and observations helped constrain simulations of climate and water use. Some scenarios indicated room for greater abstraction at the cost of lower groundwater levels or reduced spring discharge. The Saxon environmental authority reported that the partners presented their findings on recharge and drinking-water supply at a closing conference. The consequences of a change in pumping could thus be examined against observations collected on both sides of the border.

Prolonged dry periods also changed the questions asked of regional maps. The groundwater drought vulnerability assessment described in 2024 by Jiří Bruthans and colleagues used relationships between rainfall, total runoff and baseflow, the part of streamflow supplied more slowly by catchment stores. Their national method considered how the contribution of baseflow changed in the driest year within the period examined. It also incorporated recorded abstractions and estimated demand in settlements where people relied on individual supplies. This linked the sensitivity of the natural resource to the use made of it. Areas with similar rainfall could consequently fall into different vulnerability classes because of geological storage, groundwater discharge or the demands placed on their aquifers.

A related investigation mapped the suitability of Czech territory for managed aquifer recharge. The T. G. Masaryk Water Research Institute reported completion of the national map in 2021, at the same scale of 1 to 50,000 used in much regional hydrogeological work. The assessment distinguished the likely feasibility and scale of projects according to the properties of the receiving formations. A viable scheme would also depend on a source of water available at the right time and of suitable quality, and on the hydraulic connection between the infiltration site and the intended abstraction. The map supplied a first comparison of locations. Site investigations could then address how much of the introduced water would remain available where it was needed.

By 2025, resource assessment increasingly took account of the variation concealed by long-term averages. Anna Hrabánková and Josef Vojtěch Datel examined four Cretaceous districts using abstraction and baseflow records for 2007–2023. Their comparison of monthly pumping with low monthly baseflow brought periods of pressure into view, particularly in the Liběchovka and Pšovka district and in the neighbouring district drained by the Obrtka and Úštěcký streams. The study also examined how the results depended on the reference period and the groundwater setting. Its findings connected the work of defining aquifers and tracing their recharge with an operational question about water left for streams during dry months. In these districts the evidence needed for that judgement lay in the joint record of wells, springs, stream gauges and abstractions.

Water Quality, Hydrochemistry and the Hydrological Consequences of Landscape Change

Water quality in the Czech Republic changed markedly in the years after 1993, although the changes were seldom as uniform as the improvement visible in the larger rivers. An industrial discharge could be reduced within a few years, while sulphur retained in a forest soil or nitrogen moving slowly through a drained agricultural catchment could continue to reach a stream long afterwards. At the same time, the movement of water through the landscape was itself changing. The loss of a forest canopy, the drainage of a meadow or the alteration of a river channel could affect the volume and timing of runoff, as well as the substances carried with it. Over the period to 2025, Czech research increasingly brought these two histories together by asking where a substance came from, how it travelled and how long it remained in the system.

The most rapid improvement followed a reduction in pollution from identifiable outlets such as factories and municipal sewers. National reporting recorded a fall of just over 92 per cent between 1993 and 2008 in the mass of pollution discharged from point sources as measured by five-day biochemical oxygen demand. The indicator measures oxygen consumed during the decomposition of organic matter under standard test conditions. Its decline signalled a reduction in the oxygen demand placed on rivers by effluents. In the first half of the 1990s, part of the reduction reflected lower industrial production. From the middle of that decade, the construction and upgrading of wastewater treatment plants contributed increasingly to the decline. The distinction mattered when researchers sought to establish how much of the improvement could be attributed to investment in treatment.

The gains were most apparent along heavily affected rivers that received large municipal or industrial discharges. Jakub Langhammer’s analysis of the Czech Elbe basin showed that the Elbe and its larger tributaries improved substantially in the 1990s, while progress in smaller streams and headwaters was less consistent. A station below a town could quickly register a treatment upgrade. A stream crossing farmland might respond to changes spread across dozens of holdings and delayed by the passage of water through soil. The geography of recovery thus depended in part on the geography of the original pollution. Improvements along the main river brought the remaining pressures in its tributaries into sharper view.

In mountain forests, changes in water chemistry had a different history. Reductions in atmospheric sulphur deposition allowed streams and lakes affected by acidification to begin recovering. Established in 1994, the GEOMON network made it possible to follow this process across a range of small forested catchments by measuring what entered in precipitation, what passed through the canopy and what left in streamwater. In many catchments, soils continued to release sulphur accumulated during earlier decades of heavy deposition. Stream acidity and dissolved aluminium nevertheless declined at strongly acidified sites, although the timing and extent of recovery varied. The records established a basis for distinguishing the continuing influence of past emissions from changes in runoff and forest biogeochemistry during subsequent decades.

The Slavkov Forest offered a particularly revealing comparison. Three small spruce-covered catchments situated within a few kilometres of one another received broadly similar

atmospheric inputs, yet their streams differed substantially in composition. The granite beneath Lysina supplied relatively few base cations through weathering, leaving the catchment susceptible to acidification. Serpentinite beneath Pluhův Bor supplied abundant magnesium, while a third catchment on amphibolite added an intermediate geological setting to the comparison. At Lysina, researchers used the observed history of deposition and stream chemistry to test a model that also reconstructed earlier conditions and explored the course of recovery. The combination of field comparison and modelling helped explain why catchments exposed to similar pollution could respond differently to the same decline in emissions.

The Bohemian Forest lakes showed how much longer biological recovery could take. Studies drawing on historical observations and modern chemical surveys documented the severity of twentieth-century acidification and the beginnings of recovery around the end of the century. The surveys covered eight lakes on both sides of the Czech–German border, allowing investigators to compare sites that shared a regional history of air pollution but differed in local conditions. Subsequent sampling between 1999 and 2019 found increases in the abundance and species richness of bottom-dwelling invertebrates, with recovery accelerating late in the record. Water chemistry helped explain these changes, alongside differences in the habitat along the shore and the capacity of species to recolonise. A chemical improvement recorded in a lake sample could precede a substantial change in the animal community by many years.

At Lake Plešné, the decline in acid deposition coincided with a disturbance of a different kind. A bark beetle outbreak killed most of the mature Norway spruce in the catchment between 2004 and 2008, and the dead timber remained in place. Observations from 1997 to 2016 followed water as it passed through the canopy, entered the lake in its tributaries and left through the outlet. The loss of foliage reduced the supply of several substances previously washed from living crowns, including potassium and dissolved organic carbon in throughfall. Meanwhile, decomposition and changes in soil nutrient cycling altered the composition of streamwater. The timing of the responses differed among nitrate, organic carbon and phosphorus, so even within one catchment the chemical effects of a single disturbance unfolded over several seasons and years.

Measurements of the water balance at Plešné added a physical explanation to this record. Comparison with the less disturbed Čertovo catchment during the main phase of dieback showed how canopy loss altered the delivery of water to the soil and how declining transpiration affected soil moisture and runoff. The change in water reaching the soil varied with elevation, partly because trees at higher sites had intercepted water from cloud and fog. The study observed a modest increase in runoff, while the comparison of recorded peaks indicated a more limited response at high flows. At Plešné, changes in water movement coincided with changes in the supply of soluble substances. A tributary could carry a different load because more water passed through the catchment, because the water acquired a different composition, or because both processes occurred together.

Agricultural research raised a related question about the legacy of land improvement. A reconstruction of nitrogen export from the upper Vltava catchment for 1900–2010 drew on observed records from the latter half of the twentieth century and on historical estimates of

agricultural inputs and drainage. The reduction in nitrogen inputs after 1989 was reflected in the longer record, but annual river export also depended on discharge and on the area fitted with agricultural drainage. The fitted model associated drainage with higher nitrogen export after accounting for the other variables. This offered a way to understand why inherited drainage networks remained relevant during the post-socialist transition, even where the intensity of fertiliser use had already changed.

A later analysis of the Vltava from 1960 to 2015 used several dissolved constituents to trace changes in the basin. Nitrate and sulphate declined after 1990 in response to changes in agricultural and atmospheric inputs, respectively, while phosphorus reflected a different combination of sources. For some constituents, the earlier relationship between concentration and river discharge also changed. Concentration measures the amount of a substance in a given volume of water, whereas the transported load depends on both concentration and the volume passing the station. A wet year can therefore carry a substantial mass downstream even when concentrations fall during high flow. Long records pairing chemistry with discharge made it possible to distinguish a sustained fall in inputs from changes associated with the relative frequency of wet and dry years.

Reservoir studies extended the analysis from the supply of nutrients to their fate after arrival. Czech researchers working with European colleagues compared the retention of phosphorus in natural lakes and reservoirs. The time water spends in a basin affects the opportunity for particles to settle and for phosphorus to be incorporated into organisms or sediments. In a reservoir, these processes can be distributed unevenly along its length, from the shallow reach where the river enters to deeper water near the dam. Retention describes the difference between what enters and what leaves over a given period. Some of the phosphorus held back can return from sediment under suitable conditions, so the retained mass and the amount permanently buried represent different quantities.

The long record at the Slapy Reservoir on the Vltava gave these processes a historical setting. From the 1960s to the early 1990s, total phosphorus concentrations rose. They declined thereafter as the catchment’s nutrient inputs changed, although summer concentrations continued to fluctuate and the fluctuations grew larger. The investigators linked this variability to differences in river inflow and the stability of thermal stratification. Under some high-flow conditions, nutrient-rich inflow could pass through the reservoir by a different route from that taken under ordinary summer conditions. A decline in annual phosphorus supply could thus coincide with seasons of high concentrations in the upper water layer. This made the timing of inflow and the reservoir’s thermal structure relevant to assessments of eutrophication.

The importance of sampling during storms became particularly evident in small agricultural catchments. A study of ten tile-drained sites used routine sampling together with automatic collections taken at shorter intervals during rainfall and runoff events. The combination showed that routine samples alone could underestimate nutrient loads, particularly those of phosphorus. Much of the annual export of phosphorus at some sites occurred during a small number of episodes, whereas nitrate was often carried more continuously in drainage water. The drains supplied a practical point at which to observe rapid transfers from cultivated slopes

to channels. Samples collected between storms could describe ordinary concentrations accurately while understating the annual mass reaching the stream.

A related study in the Bohemian–Moravian Highlands examined pesticide transport through drains by distinguishing recently arrived rainwater from water already stored in the catchment. Chemical sampling and isotopic separation of runoff components gave the investigators a way to relate the appearance of particular compounds to the route taken by the water. Recently applied active ingredients could be carried out during an event in a relatively small portion of new water. Some degradation products were also present in drainage fed by older water and persisted between storms. The distinction helped explain why a sampling programme designed to detect short-lived pulses would record a different aspect of exposure from one designed to follow contaminants present over much of the year.

This knowledge was gradually incorporated into the spatial design of soil and water conservation. In the Jihlava basin above the Dalešice Reservoir, researchers combined assessments of erosion with information on infiltration, drainage and the position of streams. Fields liable to lose soil by surface runoff called for different measures from those where water readily percolated and carried dissolved substances towards drains. The atlas of diffuse pollution developed for the Vltava basin carried the same reasoning to a larger area by mapping pathways for sediment and nutrients alongside the risks associated with subsurface losses. Such mapping placed the field, the drain and the receiving stream within a common framework. It also gave practical meaning to the distinction between the place where a pollutant originated and the place where a measure might intercept it.

Changes to rivers and floodplains affected the route that sediment followed once it reached a channel. Research on the 2002 flood in the Otava basin compared the distribution of erosion and deposition with records of land use and with changes to channels and floodplains. Channel shortening and alterations to floodplain space helped explain local differences in the consequences of the event. The evidence was particularly informative about where fast-flowing water eroded material and where it laid that material down again. For water-quality research, the same spatial evidence was relevant because nutrients and some contaminants travel attached to fine particles. Engineering works or changes in floodplain use could therefore influence the location and timing of their transfer downstream.

The Bílina in north-western Bohemia illustrated the persistence of industrial pollution in river deposits. A long-term investigation measured metals and organic contaminants in the water, bottom sediment and biofilms attached to submerged surfaces. Substances that were difficult to quantify in a water sample could still be detected in the other two compartments, sometimes at sites with a long history of industrial and mining pressure. A sample of the flowing water described conditions at the moment of collection, while deposits and biofilms recorded a different aspect of exposure. The International Commission for the Protection of the Elbe incorporated sediment into basin-wide management through its 2014 sediment management concept. It gave Czech and German institutions a shared basis for considering the movement of sediment and the possible remobilisation of contaminants during floods or works in the channel.

A different set of hydrological questions accompanied the restoration of formerly drained wetlands. Over the period 1999–2024, work in the Šumava region blocked 296 kilometres of drainage channels and restored stretches of small streams and areas around springs. Raising the local water table and redirecting flow from ditches into wetland soils were central to the work. Measurements at each restored site establish how the water table, discharge and residence time respond. Those changes may also alter conditions for decomposition and the movement of dissolved organic matter. A rise in wetland water levels and a change in the chemistry of the receiving stream are therefore distinct outcomes, each requiring observations at the appropriate scale.

The restoration of the Teplice stream in the White Carpathians provided an early example of monitoring that distinguished changes after intervention from variation in weather. Measurements began before the works in 2020. The subsequent observations indicated a fall in runoff over the initial period examined, although differences in rainfall complicated the attribution of that fall to the restoration. The researchers considered changes in infiltration and evaporation, whose relative contributions remained unresolved. This type of record is valuable precisely because the effects of a new channel and of a dry season can resemble one another in a short discharge series. Parallel observations of precipitation, water levels and downstream chemistry can help separate these processes over a longer period.

By the early 2020s, investigations of drinking-water reservoirs were adding passive sampling to surveys of pesticide inputs. Work in the catchments of Vír I, Opatovice and Ludkovice used samplers that accumulate compounds during deployment. The devices recorded exposure over several weeks and helped detect substances whose passage through a tributary might be missed between scheduled visits. Discrete samples still had a role in establishing concentration at a particular time, especially when taken together with a discharge measurement. Combining the methods helped account for the timing of pesticide application and rainfall and for rapid pathways to streams.

By 2025, the Czech Hydrometeorological Institute’s reporting placed observations of dissolved and particle-associated pollution alongside one another. Its hydrological yearbook for 2024 reported nutrient and organic pollution indicators in surface water and considered contaminants in suspended matter and bottom sediment. These records differ in the periods and processes they represent. Material suspended during a rise in flow can indicate what a river is actively transporting, whereas bed material can retain part of the history of contamination at a particular reach. The continuing occurrence of elevated phosphorus and of organic contaminants in certain parts of the network showed why improvements in oxygen demand had to be interpreted alongside other indicators. A change in one measure could leave important ecological pressures visible in others.

The historical perspective remained productive to the end of the period. In 2025, Josef K. Fuksa compared water-quality observations from the lower Czech Elbe and the Vltava for 1961–2020 with analyses made between 1880 and 1913. The modern series showed how ammoniacal nitrogen fell after 1990 towards levels comparable with the earlier observations, while nitrate continued to make a substantial contribution to the river’s nitrogen export. Comparing wastewater treatment discharges with transport in the river helped clarify the importance of

diffuse sources. Measurements made more than a century apart required care in interpretation, yet they gave different meanings to the apparent recovery of the same river. The reduction in ammoniacal nitrogen told much of the story of sewage treatment. The persistence of nitrate led back into the catchment, to agricultural soils and the paths by which water still drains them.

Major Hydrological Achievements, Research Centres, Leading Scientists and Landmark Publications

A flood mark on a Prague wall and a soil moisture probe in the Šumava belong to the same history of Czech hydrology. Each extends the reach of observation in a different direction. The mark carries evidence of a river's behaviour across centuries, while the probe reveals changes within a few hours beneath a forest floor. Between 1993 and 2025, Czech researchers made advances by working across these differences in scale. National institutes-maintained records and issued assessments, universities developed methods for interpreting them, and teams at experimental sites observed processes that a river gauge could register only in aggregate. Their most durable achievements include flood chronologies, field records, methods for estimating uncertainty and datasets that other researchers can use to test their own explanations.

Bohumír Janský's 1997 account of geographical hydrology at Charles University captured a change in what a geographer was expected to do with water observations. The article traced a tradition of lake surveying alongside the development of more quantitative work on runoff, water quality and the character of catchments. Its historical discussion acknowledged that training in statistics and the practical use of hydrological records had once been comparatively weak at Albertov, the university's geographical centre in Prague. By the 1990s, field measurement and quantitative analysis had become integral to the work described there. The geographer's attention to the configuration and history of a catchment acquired greater explanatory force once it could be tested against measurements of flow and water quality.

Lakes remained a distinctive part of this Prague tradition. In 2004, Janský and Miroslav Šobr published a classification of Czech lakes by the origin of their basins. Glacial erosion, the activity of rivers, karst processes, landslides and human excavation could all leave standing water, yet each produced a basin with a different history and a different relation to its surroundings. Classifying the sites in this way gave field surveys a basis for comparison and widened the geographical remit of lake research beyond the well-known mountain lakes. The method was particularly apt for a country where many water bodies owe their form to human activity. It also encouraged readers of a depth map to ask what had shaped the basin and how it was likely to change.

This experience travelled beyond Czechia. In the Tien Shan of Kyrgyzstan, Janský, Šobr and Zbyněk Engel studied lakes whose formation and possible drainage were linked to glacier retreat and the behaviour of moraines. Their 2010 paper in *Limnologica* showed how field observations of a lake and its retaining structures could be read alongside imagery of changing

glacier margins. A map of a lake’s expansion could establish where and when the surface had grown. Estimating the danger to downstream valleys required further evidence on the material and condition of the barrier and on possible drainage routes. The study extended a Czech practice of close observation of lake basins into an international field of research on sudden releases of water.

A different achievement of the early period was Šárka Blažková’s work with Keith Beven on flood frequency. Their 1997 study combined a stochastic rainfall model with TOPMODEL to investigate flood peaks in Czech catchments where records alone offered few examples of rare extremes. The approach generated plausible rainfall sequences and passed them through a model of how the catchment produced runoff. It thereby made assumptions about rainfall and soil saturation explicit in the estimate of flood frequency. A later study of the Skalka catchment, published in 2009, gave greater attention to the range of model results compatible with observed behaviour. Together the papers show how a practical Czech problem contributed to international research on the uncertainty of estimates used in engineering design.

Czech and German collaboration on the Elbe gave major floods a common basin-wide record. The International Commission for the Protection of the Elbe published a joint documentation of the August 2002 flood in 2004. Its later German-language account of the 1996–2010 action programme placed that documentation alongside work on flood causes, forecasting and protection. Looking at the Vltava and the Elbe as one river system made it possible to follow the event through changes of name and jurisdiction. A shared account also gave forecasters and researchers a way to compare the timing and magnitude of peaks across the border. The resulting publications recorded how work on a single disaster became part of a longer exchange of hydrological information.

In Brno, Rudolf Brázdil and Petr Dobrovolný of Masaryk University worked with Libor Elleder and other specialists to bring historical evidence into the assessment of floods. Their 2005 monograph on historical and contemporary floods in the Czech Republic compared documentary chronologies with instrumental observations at five river profiles, including the Vltava at Prague, the Elbe at Děčín and the Morava at Kroměříž. Each source had to be interpreted in the light of what it actually recorded. A description of water entering streets could help place a flood in relation to a known level. A series of gauge readings permitted a more direct comparison, subject to changes in the channel and in the observing station. The book gave these kinds of evidence a common frame without requiring them to have the same precision.

Elleder developed the Prague evidence further in a 2015 study of changes in the frequency of extreme floods. The paper added 187 estimated historical flood peaks from 1118–1824 to the instrumental record and examined how major events clustered in time. Urban development made the reconstruction unusually demanding. A recorded water level had to be related to the city and river channel of its own day, since structures and the configuration of the banks could change the height reached by a given flow. The achievement was to turn records left for many different purposes into evidence that could inform a hydrological frequency analysis. For Prague, this made the sequence of recent floods part of a much longer and uneven history of extreme events.

The Czech Hydrometeorological Institute contributed a complementary kind of continuity. Its hydrological yearbooks organised observations of river flow, groundwater and water quality against longer reference periods. Its event reports documented how the measurements had been obtained and interpreted when conditions departed sharply from those references. The English-language account of the June 2013 floods, edited by Jan Daňhelka, Jan Kubát, Pavel Šercl and Radek Čekal, made a detailed national investigation available beyond Czech-speaking readers. The report drew its value from the relationship between observations, the chronology of the floods and an account of forecasting and warnings. As successive events were documented in this way, researchers could compare both the behaviour of rivers and changes in the service responsible for observing them.

The Academy's Institute of Hydrodynamics offered a different setting in which to build continuity. At Liz, in the upper Volyňka basin, experiments and monitoring linked observations of stream discharge to measurements in soils and vegetation. Miroslav Tesař, Josef Balek and Miloslav Šír documented this work in a Czech-language article in the Slovak-based *Journal of Hydrology and Hydromechanics* in 2006. Their account drew together successive phases of field research and examined how storage and release within the catchment moderated its response to weather. The publication preserved the reasoning behind the layout and operation of the experiments. This mattered because a long discharge series is easier to interpret when records are also available for changes in the conditions under which runoff was generated.

Experimental work at the Czech Technical University in Prague brought engineering models into close contact with observations on hillslopes. At the Uhlířská catchment, Tomáš Vogel, Martin Šanda and their colleagues used oxygen-18 to investigate the part played by preferential flow in runoff generation. It provided a check on whether a model that reproduced a rise in discharge also represented where the water had come from. Jaromír Dušek and Vogel then used simulations in a 2019 study to examine travel times for water leaving a forested slope by several routes, including stormflow, deep percolation and transpiration. Considering these routes together brought the rapid response of a stream into the same analysis as water stored in soils or returned to the atmosphere by trees.

Josef Křeček's group at the Czech Technical University followed a related line of enquiry at the Jizerka catchment. In work with Ladislav Palán, Eva Pažourková and Evžen Stuchlík, observations of rain, fog and stream chemistry were combined with forest inventories and satellite imagery. The long observation period covered substantial changes in both atmospheric pollution and forest cover. Reconstructing the forest helped the investigators interpret changes in the amount of polluted moisture intercepted by the canopy, and stream samples showed how those changes were expressed at the catchment outlet. The work exemplified a strand of Czech forest hydrology in which a record begun to investigate pollution could also be used to examine the consequences of changing vegetation and forestry practice.

In České Budějovice, the Institute of Hydrobiology maintained a tradition of long-term reservoir research initiated by Jaroslav Hrbáček. Regular investigations of the Slapy Reservoir date from 1959 and continued to supply evidence during the period covered here. Josef Hejzlar and Jiří Kopáček, working with colleagues in Czechia and abroad, used that inheritance to relate the history of nutrient supply to changes within the reservoir itself. A study with Yuliya Vystavna in

2017 drew on more than half a century of phosphorus observations. Having measurements from before and after the economic transition made it possible to follow the reversal of a long rise in concentrations and to examine the variability that persisted after inputs fell. The strength of the publication lay in the questions that such an unusually long series made possible.

Hydrogeology supplied another example of a Czech contribution with a wider readership. Jiří Krásný's 1993 classification of transmissivity offered a common way to describe the magnitude and variability of the capacity of aquifers to transmit water. A classification was useful for regional comparison because it made clear what was being compared even where the available boreholes differed in number and distribution. Krásný subsequently co-edited *Groundwater in Fractured Rocks* with John M. Sharp Jr. The volume grew out of a conference held in Prague in 2003 and appeared in 2007. It brought Czech investigations into discussion with international work on groundwater in rock masses whose productivity depends on the distribution and connectivity of fractures.

The Czech Geological Survey turned regional hydrogeological knowledge into a practical resource through its 2010–2016 reassessment of groundwater resources, known as Rebilance. Work on selected hydrogeological districts assembled geological information, measurements and water balances to revisit earlier estimates. Investigations took account of the connection between aquifers and surface waters, an essential consideration where groundwater sustains streamflow. The project's district reports gave resource figures a documented geological and hydrological basis that could be examined separately for each area. Along the Czech–Saxon border, the later ResiBil project addressed a related difficulty. Geological formations and groundwater flow crossed a boundary at which the records and maps had been compiled by different authorities. Reconstructing the aquifers jointly made it possible to examine resource questions across the area that supplied the water.

At the T. G. Masaryk Water Research Institute, the BILAN model became a means of comparing catchments with very different data and water regimes. Ladislav Kašpárek helped develop Czech work on water balances, and Martin Hanel and Adam Vizina extended its use for regional assessments of climate impacts. A 2012 study with Petr Máca and Jiří Pavlásek applied BILAN to 250 catchments using several climate scenarios. Its design made the consequences of different climate projections visible within a common hydrological framework. For water managers, the spread of results mattered alongside their average. A long-term projection gained practical meaning when it could be related to the size, location and seasonal regime of the catchment on which a supply depended.

Czech University of Life Sciences Prague became a centre for hydrological research on drought across longer periods and larger territories. In 2019, Vojtěch Moravec, Yannis Markonis, Oldřich Rakovec, Rohini Kumar and Martin Hanel published a European inventory covering 1766–2015, based on an ensemble of hydrological simulations. The study distinguished droughts in precipitation, soils and streamflow, whose severity and timing could differ during the same episode. It also made uncertainty in reconstruction part of the comparison. The inventory gave researchers working on recent Czech droughts a means of examining how far comparable events extended across Europe and how often different forms of water shortage had occurred together in the past.

Rakovec and colleagues took the comparison further in their 2022 assessment of the European drought of 2018–2020, a collaboration involving the Czech University of Life Sciences and the Helmholtz Centre for Environmental Research in Germany. In the study's reconstruction, the persistence and intensity of the episode stood out over roughly two and a half centuries. The warmth accompanying the water deficit was a particularly marked feature. Treating successive dry seasons as parts of one event made it possible to investigate a problem that annual summaries could obscure. Soil water and river flows can begin a new season with the effects of earlier deficits still apparent. This longer view changed the terms in which Czech and European droughts could be compared.

Mountain hydrology at Charles University provided a corresponding achievement at the seasonal scale. Michal Jeníček and Ondřej Ledvinka's 2020 work on Czech catchments estimated the contribution of melting snow to river flow and examined the consequences for summer low flows. In many of the catchments studied, a larger fraction of annual runoff came from snowmelt than would be suggested by the proportion of precipitation that fell as snow. The timing of recharge and the losses to evapotranspiration helped explain the difference. The paper provided a way to interpret winter and summer records together and placed mid-elevation Central European mountains within a wider discussion of how a declining winter snow store changes water availability.

The connections between researchers and operational services became more visible in the publications of the 2020s. The *Flash Flood Indicator* monograph, published in 2023 by Šercl and colleagues at the Czech Hydrometeorological Institute, described how rainfall estimates and antecedent conditions were used to assess the potential for rapid runoff in small catchments. Publishing the method exposed the reasoning behind an operational product to scrutiny by readers beyond the forecasting office. At a different time scale, the published account of the HAMR drought system brought together the Water Research Institute, Czech University of Life Sciences, CzechGlobe and the Hydrometeorological Institute. The two publications document an achievement that is easy to overlook in a history of journal articles. Research methods became procedures that could be maintained and used while an event was unfolding.

By 2025, access to records had become an achievement in its own right. The Czech law on public hydrometeorological services, which took effect that year, established a national database of hydrometeorological data and products. A complementary example of reuse was CAMELS-CZ, curated by Jakub Krejčí with Grey Nearing using Czech observations and other data sources. The 2025 release paired discharge series with meteorological inputs and documented catchment attributes, making it easier to compare model performance across the country and to connect Czech sites to international large-sample studies. Researchers could begin with comparable inputs, then look back to station histories and field studies to explain the catchments that behaved differently.

The research centres had changed alongside the methods they sustained. In April 2025, the Academy's Academic Council resolved that the Institute of Hydrodynamics would take the name Institute of Hydrology from the beginning of 2026. The decision recognised the direction already taken by its research, including the study of water in soils, catchments and vegetation.

Elsewhere, groundwater assessment, reservoir science, hydrological forecasting and the reconstruction of historical extremes retained their own institutional homes. By the end of the period, a study of a Czech river could draw on an archive of levels and floods, a documented set of catchment observations and models whose performance could be examined across many basins. These resources made it possible to revisit an old result when a longer record or a better measurement changed the interpretation.

Part Eight

Economic Geography and Regional Development

Economic Geography after 1993: Post-Socialist Transformation and the Renewal of Regional Development Theory

A map of the Czech economy drawn in 1993 would have shown a country whose inherited industrial geography was still recognisable, but whose rules of development had changed almost overnight. State enterprises were being privatised, foreign trade was turning towards Western Europe, and local authorities were learning to operate without the administrative certainties of central planning. The pattern of factories, towns and transport routes could not be remade as quickly as the institutions governing them. For economic geographers, this uneven pace created a rare opportunity to observe how established territorial structures responded to a change in the organisation of economic life. During the following three decades, Czech research moved from documenting the geography of transition towards explaining regional development through institutions, networks, knowledge, historical trajectories and the decisions of particular actors. The shift was neither abrupt nor complete. It grew from a continuing argument about which features of Czech regional differentiation were historically persistent, which were products of socialism and which arose from the market economy established after 1989.

The geographical disciplines entering the new republic had a more substantial intellectual inheritance than the political rupture might suggest. Research into settlement hierarchies, the distribution of population, regional systems and the organisation of society had been pursued under socialism, notably at the Faculty of Science of Charles University. Martin Hampl's interest in the hierarchical organisation of socio-geographical systems had developed before 1993 and remained important afterwards. The communist period nevertheless constrained access to some international debates and limited the subjects that could be investigated openly. Work on market competition, regional inequalities produced by investment decisions and the geography of private enterprise acquired a different significance once these became everyday features of the national economy. The renewal of economic geography thus involved recovering the freedom to choose research questions while retaining methods and observations that had already proved their value. An intellectual tradition concerned with spatial order was brought into conversation with theories developed in capitalist economies.

The dissolution of Czechoslovakia on 1 January 1993 defined a new national unit for statistical comparison and regional policy, but the decisive economic transformation had begun earlier. Price liberalisation, the privatisation of businesses and changes to external trade affected a territory that had entered the 1990s with a relatively compressed distribution of wages and several heavily industrialised districts. The consequences were visible at different scales. Prague attracted advanced services and managerial activities, manufacturing districts

confronted changing demand, and smaller towns had to replace functions once supplied by large employers. Border location could become an advantage where firms gained access to new markets, yet proximity alone could not compensate for obsolete equipment or weak entrepreneurship. These processes made geography more than a description of uneven outcomes. They required researchers to ask how the inherited specialisation of places interacted with national decisions, external demand and the capacities of local institutions.

An early problem was the interpretation of inequality itself. Low national unemployment during the first years of transformation could suggest that Czech regional disparities were modest, especially when compared with more severely disrupted post-socialist economies. Jiří Blažek's 1996 study of inter-regional differences cautioned against such a reading. It compared several indicators and showed why a single national average, or even one conventional measure of dispersion, could conceal meaningful territorial differentiation. Differences in business formation, earnings and economic performance did not necessarily move together. A region might maintain employment while losing relatively productive activities, or show improving incomes without developing a correspondingly strong local enterprise base. The study helped establish a question that recurred in later Czech scholarship: whether convergence or divergence was being measured, and exactly which part of regional development the chosen indicator represented.

Martin Hampl and his colleagues approached the same upheaval from the longer history of geographical organisation. The 1996 volume on the geographical organisation of society and transformation processes placed contemporary change within a framework of settlement systems, functional hierarchies and spatial concentration. Its underlying argument was that transformation did not take place on an empty territorial surface. The uneven distribution of administrative functions, skilled labour and economic command had accumulated over a much longer period than the current political order. Liberalisation could therefore strengthen some established centres while exposing the vulnerability of places formerly protected by state priorities. This approach differed from explanations that treated each region simply as an isolated collection of firms or workers. It regarded regions as parts of interdependent national systems in which a gain in one location might be accompanied by the relocation or loss of functions elsewhere.

Research published in 1999 and 2001 extended that interpretative project. The English-language Geography of Societal Transformation in the Czech Republic made the country's experience available to a wider audience, while Hampl's 2001 volume on regional development addressed the relationship between Czech transformation, European integration and general theory. Both works treated the post-socialist case as evidence capable of testing wider geographical propositions rather than as an exceptional episode beyond comparison. In that respect, the opening of international scholarly exchange mattered as much as a larger circulation of publications. Czech geographical analysis could be placed beside studies of industrial decline, metropolitan concentration and regional restructuring elsewhere in Europe. The comparison encouraged a distinction between the extraordinary speed of institutional change after 1989 and the more familiar long-term tendencies towards spatial selectivity and concentration.

The concern with explanation also changed the place of theory in the discipline. In his 1999 article ‘Regional Development Theories: A Vicious Circle?’, Blažek examined approaches that made contrary predictions about the future of regional disparities. Neoclassical accounts emphasised the potential for adjustment through mobility and market competition; cumulative and structural approaches were more attentive to processes that reinforce an initial advantage. Other traditions placed the state, institutions or innovation at the centre of regional change. The significance of the discussion lay in refusing to choose a theory merely because it fitted the political climate of the period. Each approach rested on assumptions about mechanisms and scales, and different indicators could appear to confirm different expectations. Czech economic geography began to treat the selection and critical comparison of theories as a research problem in its own right.

That effort reached a wider readership through the successive editions of Jiří Blažek and David Uhlíř’s Teorie regionálního rozvoje. The first edition, published by Karolinum in 2002, offered a systematic introduction to regional development theories at a time when Czech teaching and policy discussion still needed a consolidated account of international scholarship. The revised and expanded 2011 edition gave substantially more attention to institutional perspectives, the new economic geography and connections between innovation and international production. A third edition appeared in 2020, by which time the discussion could incorporate global value chains, regional innovation systems and smart specialisation as established elements of the field. These publications do more than mark the arrival of successive fashions. Read together, they document a sustained attempt to assess what different theories could explain in the Czech setting, which concepts could travel across national contexts and where their policy implications remained uncertain.

The expansion of available evidence supported this theoretical renewal, although it also produced problems of comparability. Regional statistics, population censuses, enterprise data, commuting records and administrative sources had not all been designed for the same territorial purposes. The restoration of regional self-government, with fourteen higher territorial units beginning to operate in 2001, created an additional level at which to discuss development. European Union statistical and policy frameworks brought yet another set of regional groupings, including the NUTS 2 cohesion regions used for many funding decisions. A result calculated for districts could differ from one calculated for kraje, and a change in boundaries could look like a change in economic performance if the underlying data were not handled carefully. Geographers increasingly had to make the choice of spatial units’ part of their argument, explaining what a map could reveal and what it could conceal.

The question of historical comparison likewise grew more important. Rudolf Štika’s 2004 investigation of regional disparities in the 1990s set the decade against evidence from the interwar Czech lands. By comparing several measures of variability, including the Gini and Theil indices, the study challenged the assumption that renewed territorial differences were wholly unprecedented. Some of the spatial patterns that became visible after the end of central planning had older foundations. At the same time, comparisons across decades required caution: the meaning of employment, economic output and the location of activity could change with both political regimes and statistical practices. The value of the longer view was

therefore analytical rather than nostalgic. It enabled scholars to distinguish a return of older spatial tendencies from the new processes associated with global integration and economic restructuring.

In an assessment published in 2000, Ivan Bičík and Hampl described the state of Czech human geography and the questions raised by its earlier scholarly isolation. Their discussion linked the sudden demand for research on societal transformation with debates about the cognitive purposes of geography. A discipline might produce detailed accounts of particular regions and still need to ask what regularities those cases revealed. Equally, a general law of spatial concentration could become misleading if it ignored the political and institutional circumstances through which concentration occurred. This tension between general explanation and geographical specificity proved productive. Economic geographers drew on economic theory, sociology and regional studies, while continuing to test their propositions against the distinctive settlement structure and administrative history of Czechia.

During the 2000s, the empirical account of transformation became more differentiated. In a 2007 study of regional disparities, Hampl examined how socio-economic development produced contrasting tendencies among social groups and territorial communities. A loss of uniformity could be expected when market competition replaced administrative equalisation, yet differences in income, economic activity and geographical concentration followed different trajectories. The interpretation depended upon whether researchers were investigating the changing distribution of resources among inhabitants or the changing distribution of economic functions among places. Such distinctions helped explain why a national economy could become more productive while the relative position of some industrial districts deteriorated. They also complicated simple claims that regional policy should either accept all forms of divergence as efficient or attempt to reverse them through uniform redistribution.

Blažek and Pavel Csank's 2007 examination of the phases of Czech regional development added a temporal qualification. Using regional gross domestic product, unemployment, entrepreneurial activity and self-employment-related tax revenue, the authors found marked divergence during the 1990s but argued that the opening phase did not continue indefinitely. Around the turn of the millennium, several measures of regional difference ceased to increase in the same way. Their analysis made it possible to discuss a period of relative stabilisation without assuming that an equal regional structure had been restored. The distinction was central to the theoretical debate. A transition shock might produce a rapid rearrangement of positions, after which the level of inequality became more persistent; a later economic crisis might then start a new episode of differentiation. Regional change had to be read as a sequence of processes rather than a single unbroken trend.

The accession of the Czech Republic to the European Union in May 2004 altered both the practical setting and the questions asked by researchers. European funding brought regional competitiveness, cohesion and the territorial effects of public intervention into closer contact with academic work. At the same time, a region receiving structural assistance was not necessarily one in which the aggregate spatial impact of state policy was most favourable. Major transport investments, education spending and other sectoral programmes could shape regional opportunities without being labelled regional policy. Researchers therefore had to

distinguish the declared objective of reducing disparities from the total territorial effect of government action. The question was no longer confined to whether a disadvantaged region qualified for support, but extended to how many separate funding decisions collectively affected its position within the national economy.

This distinction was developed empirically by Blažek and Marie Macešková in a 2010 article in Regional Studies. They assembled evidence on Czech public capital expenditure for 1995–2005 and compared the location of sectoral investment with the pattern of areas targeted by regional assistance. The research exposed an important mismatch between the spatial effects of public expenditure and the purposes of explicit regional policy. A small programme designed to support a weaker territory could be outweighed by infrastructure or institutional investments that primarily benefited already successful centres. For the development of Czech economic geography, the study demonstrated how a theoretical concern with uneven growth could be translated into a question answerable with difficult administrative data. It also introduced territorial impact assessment as a means of scrutinising policies that were not presented as geographical decisions.

The growing sophistication of regional analysis did not eliminate disagreement over what constituted a valid explanation. A correlation between proximity to Prague and favourable employment outcomes might be strong, yet it could not by itself establish which institutions, firms or decisions produced that outcome. Hampl, Blažek and Pavla Žížalová addressed this difficulty in their 2008 discussion of factors, mechanisms and processes in regional development. Drawing on critical realism, they distinguished the observed pattern from the causal mechanisms that might generate it. A factor such as educational attainment could be important without operating in an identical way everywhere. Its effects might depend on enterprise organisation, labour-market institutions or the capacity of local actors to use available knowledge. The conceptual shift encouraged research designs that combined statistical regularities with investigation of how particular outcomes arose.

Methodological development followed a related path. Pavlína Netrdová and Vojtěch Nosek examined the geographical dimension of societal inequalities in a 2009 study comparing measures of inequality decomposition with spatial autocorrelation. Their work showed that it was possible to identify an unequal distribution without establishing whether similar values clustered geographically. A high degree of dispersion need not imply the same spatial arrangement as a contiguous zone of disadvantage. Conversely, neighbouring municipalities could resemble each other while a national measure registered only moderate inequality. This mattered for economic geography because the territory at which an intervention could operate depended partly on the pattern being measured. The analysis moved beyond colour-coded regional rankings towards a more explicit treatment of spatial dependence, aggregation and the limits of each statistical index.

A deeper question concerned the relationship between concentration and development. Hampl’s 2010 article on the regional differentiation of society revisited general types of development processes and the varying forms of concentration found in complex social systems. The argument resisted the idea that every aspect of development followed the same trajectory towards convergence or divergence. Population, functions and other measures

could be redistributed at different speeds, and periods of reorganisation could alternate with relative stabilisation. Such reasoning had particular relevance to the Czech case, where metropolitan command functions could increase while residents moved into surrounding municipalities or where employment levels stabilised without restoring the earlier industrial structure. The study continued an older Czech theoretical tradition while applying its concepts to the evidence accumulated after the end of socialism.

Hampl and Jan Müller's 2011 research on the changing distribution of jobs and population made the difference between these dimensions especially clear. Employment and inhabitants do not respond simultaneously to changing opportunities. A new workplace may attract commuters long before it changes settlement patterns, while a residential move can leave a person's daily economic relations anchored in another district. The authors used the distribution of jobs and population to examine the changing geography of Czech society after transformation. Their work demonstrated that the degree of concentration depended on which phenomenon was mapped. It also offered an important warning against treating residence-based statistics as a complete account of economic activity. A region's position in the national division of labour may be better indicated by the functions it performs than by the number of people living within its boundaries.

The global financial crisis of 2008–2009 supplied a further test. As external demand weakened, regions with apparently similar unemployment before the downturn could experience very different shocks. Blažek and Netrdová's comparison of unemployment effects across the new Central and Eastern European members of the European Union placed Czech experience within a broader regional field. Their analysis drew attention to the vulnerability created by particular economic specialisations and to the varied territorial consequences of an internationally transmitted crisis. It also showed why regional resilience cannot be inferred solely from performance in a period of expansion. A region that grew rapidly through favourable external conditions might face greater adjustment when those conditions reversed. Questions about long-term development consequently began to include the capacity to absorb disturbances and to alter existing trajectories.

At a finer spatial scale, Blažek and Netrdová's 2012 study of local differentiation asked whether the Czech economy was becoming a more intricate territorial mosaic. The approach questioned the adequacy of comparisons among large administrative regions. Within a prosperous kraj, some municipalities could remain economically vulnerable; within a disadvantaged one, a small number of towns could gain new functions and investment. Measuring the evolution of inequality at several scales revealed different dimensions of territorial change. It also required careful interpretation of spatial fragmentation: a patchwork of local outcomes might reflect access to a transport corridor, the legacy of a particular employer or selective movements of workers and households. The increasingly detailed mapping of economic processes brought the discipline closer to local experience without abandoning the search for wider regularities.

The new economic geography and institutional theories offered contrasting but potentially complementary explanations of these patterns. Models of increasing returns, transport costs and market access helped clarify why economic activity could cluster even when mobility and

competition were present. Institutional perspectives drew attention to trust, coordination, public organisations and the capacities of firms to learn. Evolutionary economic geography added the proposition that opportunities were shaped by earlier specialisations and accumulated competencies. These approaches were not simply imported into Czech textbooks. They were compared with empirical questions arising from the country's industrial inheritance, regional hierarchy and integration into European production. A successful theoretical renewal required explaining why the same external opportunity could lead to different results in two localities with broadly comparable initial resources.

Blažek's 2012 article on regional innovation systems and global production networks offered a particularly clear statement of this intellectual development. It examined two prominent perspectives on competitiveness and considered how they related to the 'Albertov School' of Czech geography. Regional innovation-system research emphasised locally organised institutions, firms and the circulation of knowledge; global production-network research examined how activities and decisions linked territories across borders. The article noted that the isolation of Czech geographical scholarship had been substantially overcome and that research questions increasingly resembled those discussed internationally. Yet it also identified imbalances and unresolved problems. The central issue was not whether the local or global perspective was correct, but how the capabilities of a region interacted with relationships that extended far beyond it. This question would become important in subsequent research on innovation and industrial restructuring.

The adoption of these perspectives changed the meaning of territorial competitiveness. It was no longer sufficient to count enterprises, compare wage levels or assume that the arrival of capital automatically transferred decision-making capacities to a region. Researchers began to distinguish the location of productive activity from the control of technology, the ability to innovate and the appropriation of value. Local institutions could help firms develop specialised knowledge, but the most consequential decisions might still be made by customers or parent companies elsewhere. Likewise, a network that brought employment to a region might restrict its capacity to diversify into more demanding functions. The institutional and network approaches made such tensions visible within the same analytical framework. They also helped prevent a simple opposition between successful metropolitan regions and unsuccessful industrial ones: the quality of their connections and capacities required independent examination.

The increasing variety of approaches was reflected in the wider geography of Czech research. Charles University's Department of Social Geography and Regional Development remained an important centre of theoretical discussion, but regional development also became a subject for teams working in Moravia, Silesia and other parts of the country. Economists, sociologists, planners and geographers collaborated on questions of investment, competitiveness, unemployment and territorial governance. This breadth created useful disagreements over whether the region should be defined as a functional labour market, an administrative unit, a network of firms or a community with shared institutions. A policy region suitable for distributing funds might not coincide with the area within which a production network

operated. The practical necessity of planning across administrative boundaries thus reinforced the methodological concern with defining spatial units according to the process being studied.

By the 2020s, the persistence of regional disadvantage had become less readily explained as a remaining consequence of the initial transition. In 2021, Filip Vrbík and Netrdová compared the trajectories of unemployment in the neighbouring Karvinsko and Jablunkovsko microregions. Their quantitative analysis and interviews revealed the value of combining evolutionary and institutional approaches with knowledge of local history. Places relatively close to one another had not followed the same path, because institutions, informal practices and previous development mattered alongside wider economic circumstances. The contrast tested a proposition that broad maps could not resolve: geographical proximity does not guarantee similar adaptation. It also demonstrated that an account of path dependence need not imply that history determines outcomes completely. Local actors can reinforce inherited practices or change how resources are used.

A closely related question came to the foreground in Blažek and Viktor Květoň's 2023 analysis of old industrial regions. Their work on two coal regions with contrasting trajectories sought to integrate several approaches to agency in regional path development. They distinguished action directed towards improving an organisation from action that changes the wider regional system. The difference is consequential: a company might modernise successfully while doing little to build regional institutions or create opportunities for other enterprises. Conversely, coordinated initiatives by firms, public authorities and other organisations might alter the conditions under which future investment decisions were made. The study found that the strength and form of system-level agency helped explain divergent regional trajectories. This was an important development from earlier comparisons of inherited regional resources, since actors' capacity to reshape those resources became part of the explanation.

Blažek, Vojtěch Kadlec and Květoň extended the agency perspective in a 2024 study of a multiply disadvantaged region. Drawing upon thirty in-depth interviews, they investigated how local enterprises acted where regional resources were limited and system-level coordination was weak. The findings distinguished entrepreneurial strategies that compensated for poor local conditions from initiatives capable of improving those conditions for a wider set of actors. The approach connected economic geography with an everyday question of policy: what can regional institutions reasonably change, and which disadvantages must individual firms overcome on their own? It also moved theoretical discussion beyond a contrast between determined structures and unrestricted individual choice. The possibilities available to a regional actor depended upon inherited assets, relationships and institutions, while some forms of collective action could gradually alter those constraints.

These advances had a visible counterpart in policy language, although scientific influence on individual decisions cannot be inferred from similarity of concepts alone. The Regional Development Strategy of the Czech Republic 2021+ distinguished metropolitan areas, agglomerations, regional centres with their rural hinterlands, structurally affected regions, and economically and socially vulnerable territories. Its differentiated territorial approach was unlike the expectation that a single development instrument would suit the entire country. The strategy recognised that places confronted contrasting combinations of growth pressures,

industrial restructuring, accessibility and institutional capacity. It also emphasised the territorial implications of sectoral policies, a question raised repeatedly in academic work. By 2025, the research agenda and the language of public planning had become connected through shared concerns over functional territories, regional potential and unequal opportunities, without ceasing to serve distinct purposes.

The three decades after 1993 therefore altered both the evidence and the explanatory ambitions of Czech economic geography. Early studies established how liberalisation and restructuring changed regional differences; later work asked why those differences persisted, changed scale or reappeared after crises. Theories of spatial concentration and regional hierarchies were not discarded when institutional and evolutionary perspectives became prominent. Instead, they were tested against new evidence about firms, networks, policies, local agency and the uneven distribution of knowledge. A continuing strength of the Czech contribution was its willingness to connect the exceptional circumstances of post-socialist transformation with questions relevant to other market economies. By the end of 2025, the field could examine a region as a historical structure, an economic system and a setting for purposeful intervention. The following sections trace how this conceptual renewal informed research on industry, global investment, innovation and the changing geography of individual economic sectors.

Industrial Restructuring, Foreign Direct Investment and Global Production Networks

In the early years of the Czech Republic, the factory was both an economic institution and a geographical inheritance. Its buildings, rail sidings and specialised labour force belonged to industrial systems assembled over generations, while its markets and means of survival were being remade. A machine works could possess considerable technical expertise yet lose the orders on which its workshops depended. A town with a newly established foreign-owned plant might meanwhile acquire customers, technologies and jobs that had not existed there a few years earlier. Between 1993 and 2025, these contrasting experiences made industrial restructuring one of the central subjects of Czech economic geography. Researchers came to see a plant not simply as a point on a map but as a workplace embedded in a locality and connected to decisions made elsewhere. The resulting scholarship linked national transformation to the changing organisation of European and global production.

The industrial landscape inherited in 1993 had been shaped by older Czech manufacturing traditions as well as by the priorities of state socialism. Mechanical engineering, metallurgy, mining, textiles, glassmaking and chemicals had provided employment across a dense system of industrial towns. Their distribution reflected mineral deposits, water and transport routes, previous investment and the location of trained workers. Central planning had added large enterprises and encouraged the concentration of particular activities in particular regions. Some factories retained valuable skills and equipment, but many were poorly positioned to

respond to new prices, competitors and quality requirements. Economists could describe the aggregate decline of an industrial branch; geographers asked where the losses occurred, which neighbouring activities depended upon the firms concerned and whether alternative employment could arise within reach of the affected population. This spatial question became increasingly urgent as the transition proceeded.

Industrial adjustment was neither an instantaneous rupture nor an orderly replacement of inefficient factories by successful ones. The first half of the 1990s brought the disruption of established trading relationships, changing demand, privatisation and attempts to reorganise ownership and management. Enterprises responded by shedding labour, separating subsidiary activities, seeking export customers or renegotiating relationships with suppliers. The direction taken depended partly on their technological capabilities and partly on access to finance and external partners. Even within a single industry, some plants survived through incremental adaptation while others lost production on which towns had long relied. A statistical change in manufacturing employment therefore concealed several different processes: genuine closures, gains in productivity, outsourcing of services and the movement of workers into new sectors. Czech industrial geography became more convincing when it distinguished these mechanisms instead of treating every reduction in factory employment as an equivalent loss of industrial capacity.

An important early synthesis came from Václav Toušek, Milan Vančura and Milan Viturka, whose study of the geographical aspects of industrial transformation appeared in Geografie in 2000. They examined the uneven fortunes of branches such as metallurgy, heavy engineering, textiles and leather production against the growth of electronics and automotive manufacturing. Their treatment of foreign investment was explicitly regional: the question was not only how much capital entered the country, but where it was placed and how its location modified inherited differences. The authors considered investment across a set of Czech towns rather than assuming that the benefits of a national reform would spread uniformly. Such work made the transition visible as a reorganisation of places as well as enterprises. It also established a useful distinction between the continuing significance of industrial heritage and the emergence of a new geography of investment.

The Ostrava–Karviná region offered one of the most demanding tests of this approach. Coal extraction, iron and steel production, heavy machinery and related infrastructure had formed an interdependent industrial complex whose physical and occupational imprint extended far beyond individual pits or works. Restructuring involved changing ownership and production at major enterprises, reducing deep mining and confronting the environmental consequences of intensive industrialisation. Petr Klusáček's 2005 study brought together developments in coal mining, steelmaking and heavy engineering, showing why they could not be examined independently. Antonín Vaishar's work on the Ostrava settlement system added another dimension: industrial restructuring altered the functions and relationships of towns whose growth had been tied to particular workplaces. Declining employment and improving some environmental conditions could occur at the same time, complicating any simple judgement of success or failure. Industrial change here demanded attention to the accumulated geography of housing, transport, land and skills.

The industrial regions of north-western Bohemia presented a related but distinct problem. Brown-coal extraction, energy production and chemical manufacturing had created concentrated economic functions and substantial environmental burdens. A reduced or reoriented industrial activity could release land without immediately making it suitable for a new investor, since contamination, infrastructure and legal responsibilities persisted. Elsewhere, in textile, footwear and glassmaking districts, the difficulties lay less in enormous extraction complexes than in the survival of specialised production traditions confronted by international competition. Towns within the same administrative region could consequently follow different paths of adaptation. Researchers who compared these areas had to consider the character of their industrial inheritance rather than apply the same regeneration prescription everywhere. The geographical legacy of transition consisted as much of uneven adaptability as of uneven production decline.

Foreign direct investment introduced another set of geographical distinctions. An acquisition of an established Czech enterprise, a joint venture and a newly constructed plant might all appear in investment statistics, yet their consequences for employment and local supply relations could differ substantially. An acquisition could preserve production and bring new technology, but it could also produce workforce reductions or the loss of headquarters functions. A greenfield project might create employment quickly while relying on imported inputs and managerial decisions made outside the region. Some investments sought access to Czech consumers; others used the country as a production location for markets further west. In an influential 1998 article, Petr Pavlínek differentiated such strategies and analysed their potential for regional development through the example of the Volkswagen–Škoda relationship. The study encouraged readers to ask what an investor intended to do with a location rather than assume that foreign ownership had a single economic meaning.

The entry of Volkswagen into Škoda Auto began before the independent Czech state was established, but its consequences became especially visible after 1993. The enterprise at Mladá Boleslav was drawn into a larger system of vehicle development, purchasing, quality control and sales. Its transformation was not merely the installation of machinery or the renewal of a familiar marque. Automotive production depends on the coordination of numerous suppliers, exacting delivery schedules and the ability to maintain product standards at scale. Decisions taken at the assembly plant could therefore change the prospects of component producers elsewhere in Czechia. The spatial effects reached beyond the district containing the factory, although the extent and quality of those links varied. For economic geographers, the case demonstrated how the future of a national industrial tradition could become tied to the organisational logic of a transnational corporation.

Investment promotion gradually became more systematic. CzechInvest, established in 1992, began the independent republic with a small staff and a mandate to attract external capital. A government investment-incentive scheme introduced in 1998, followed by the Investment Incentives Act of 2000, made the conditions for support more regular and visible. Public measures included fiscal relief and assistance associated with employment, training and the preparation of industrial sites. After European Union accession in 2004, investment and enterprise support operated within a more elaborate European policy framework. The

geographical question was whether the resulting projects would reinforce already attractive locations or provide viable employment in disadvantaged districts. Incentives could reduce the immediate cost of a project, but they could not by themselves determine how locally embedded the investor would become. Their effectiveness therefore required assessment beyond announced commitments or ceremonial openings.

Industrial zones changed the practical geography of investment. Local authorities and central institutions helped prepare plots with road access, utilities and administrative arrangements suitable for modern production. For firms choosing between several countries or towns, the availability of an operational site could matter as much as the local wage level. Such preparation sometimes brought substantial employment to places with a weakening industrial base. Yet the difference between developing a greenfield location and reusing an obsolete industrial site was consequential: the former could be faster, while the latter might address the long-term costs of earlier production. Site preparation also transferred some risks to public bodies, whose expenditure preceded the eventual performance of individual investors. For researchers, the industrial zone became an object of study in its own right, situated between local planning, regional competition and the location strategies of mobile capital.

The attraction of manufacturers from Western Europe, North America and Asia did not produce a uniform new industrial map. Proximity to the German market and major transport corridors favoured some western and central locations, while established labour pools and available land drew projects to others. The Czech industrial labour force combined relatively developed technical skills with wage costs lower than those in much of Western Europe. This combination was valuable to firms reorganising European production without moving far from their principal customers. Nevertheless, a skilled workforce in a town did not guarantee an investment if the requisite site, infrastructure, suppliers or administrative arrangements were missing. Geographers consequently began to examine location as the outcome of several interacting conditions. The distribution of foreign-owned establishments became evidence both of international corporate strategies and of the uneven capacities of Czech localities to respond to them.

The automotive industry proved especially important because an assembly investment generated demand for a wide range of other activities. Producers of seats, glass, tyres, wiring systems, plastic components, metal parts and electronics could be drawn into supplier networks organised around deliveries to a vehicle manufacturer. Some suppliers followed existing customers into the Czech Republic, bringing management and technology from their overseas operations. Others were Czech enterprises attempting to meet unfamiliar standards or retain a position in a restructured purchasing system. Petr Pavlínek's 2003 investigation of automotive components described how price liberalisation, changing markets and Volkswagen's investment in Škoda affected these relationships. The account showed that the apparently simple category of 'industrial modernisation' included difficult negotiations over quality, cost and control. The new supplier geography was made through relationships between firms, not just through the spatial addition of factories.

This development also changed the scale at which Czech manufacturing could be understood. The nation-state remained important for taxation, labour markets and investment policy, but

an automobile assembled in Czechia increasingly depended on decisions and components originating in several countries. A plant might supply customers across Central Europe while its purchasing policy was set at corporate headquarters abroad. Its apparent local success could therefore coexist with a limited ability to influence product design or market strategy. Research on global value chains and global production networks gave economic geographers a language for tracing these connections. It distinguished the activities performed in a locality from the governance relationships through which firms secured orders and allocated functions. Czech manufacturing could then be analysed as a differentiated position within international systems, rather than as a self-contained national sector.

The distinction between global value chains and global production networks was more than terminological. A value-chain analysis can reveal how the successive stages of making a product are coordinated and where functions of differing complexity are located. A production-network perspective also invites attention to institutions, bargaining power, workers, territory and the relations connecting firms at several scales. For the Czech case, this widened the interpretation of investment beyond capital inflow and export volume. A supplier might increase output but remain dependent on a small number of customers; another might acquire technological capabilities without gaining influence over strategic decisions. The central issue became whether insertion into an international production system improved the position of firms and regions over time. That question could not be answered solely from employment figures or the number of products leaving a factory gate.

The work of Pavlínek, Bolesław Domański and Robert Guzik in 2009 demonstrated the benefits of comparing Central European automotive industries within this wider framework. By examining changing production and trade alongside design and local sourcing, the researchers distinguished several forms of industrial upgrading. Process upgrading meant producing more efficiently or reliably; product upgrading concerned the technical or market characteristics of what was made; functional upgrading referred to the acquisition of activities such as development, engineering or higher-level coordination. These changes were related but not interchangeable. A Czech plant could install highly advanced equipment and achieve international standards while retaining little authority over what it produced or how new products were conceived. The comparison made it possible to recognise substantial achievement without confusing modern factory production with equal influence over the whole automotive business.

Firm-level evidence gave the argument greater precision. In a study published in the Journal of Economic Geography in 2011, Pavlínek and Jan Ženka examined the development of 490 Czech-based automotive firms during a period of major foreign investment. Their findings pointed to selective upgrading rather than an undifferentiated movement of the industry towards more valuable functions. Ownership, supplier position and corporate organisation affected what improvements were possible. The same national manufacturing expansion could therefore contain plants improving their production processes, firms moving into more demanding components and enterprises unable to escape low-margin activities. This did not make technological progress illusory; it made its distribution an empirical question. The study

helped shift Czech industrial geography from measuring the expansion of a branch to analysing differentiated trajectories within that branch.

A further difficulty was the relationship between a plant's productivity and the benefits retained in its host region. Value added measures what production creates in economic terms, but not automatically what remains available to local workers, suppliers or public authorities. Wages, taxes, purchases from domestic enterprises and reinvested earnings offer different channels through which a region may benefit. Dividends and other financial flows can connect the same activity to owners elsewhere. Pavlínek and Ženka's 2016 study of automotive value creation and capture compared supplier tiers and ownership groups using firm-level evidence. Higher-tier firms often generated greater value per worker, whereas lower-tier suppliers could be important sources of employment relative to production. The analysis challenged the assumption that the most productive plant necessarily delivers the largest range of regional benefits. It provided a more differentiated way to evaluate industrial success.

The problem of supplier linkages lay at the centre of this interpretation. Large foreign-owned enterprises can purchase locally and thereby support training, investment and the growth of domestic firms. Yet proximity does not ensure that a Czech supplier will enter a multinational company's purchasing system. Price requirements, certification, scale, delivery reliability and decisions made by corporate procurement departments may all create obstacles. A 2016 study by Pavlínek and Pavla Žížalová drew on surveys and interviews with foreign- and Czech-owned automotive companies to examine such links and their consequences. It found that domestic firms had unequal capacities to benefit from relationships with foreign investors. Knowledge transfer could occur, but its scope depended on a supplier's capabilities and its place in the network. This placed local enterprise development alongside the study of foreign investment, rather than treating it as an automatic consequence.

Geography also matters within the supplier hierarchy. An assembly plant draws specialised contractors and logistics operators into its orbit, but the resulting economic effects do not spread evenly from the vehicle manufacturer across surrounding districts. Some components must be delivered in highly synchronised sequences, encouraging the presence of nearby operations. Standardised goods may be sourced from more distant factories, and procurement structures can weaken the connection between an industrial region and the firms physically located there. In 2013, Jan Ženka and Pavlínek compared the regional effects of upgrading within Czech automotive production networks between 1998 and 2008. Their analysis distinguished areas hosting assembly operations from those dominated by component manufacturing and assessed their differing capacity to retain value. The regional map of an export-oriented industry thus appeared not as a single successful corridor but as a hierarchy of places with unequal economic functions.

Manufacturing branches outside vehicle production raised similar questions, although their technical and geographical requirements differed. Electronics attracted foreign producers and contract manufacturers whose customer relationships could change rapidly. Mechanical engineering retained firms with deep local expertise, while internationally owned enterprises became important in machinery, electrical equipment and industrial services. The character of investment varied from labour-intensive assembly to the production of complex

components for specialised markets. Researchers therefore needed to avoid treating the automotive industry as a complete model of Czech industrialisation. Its scale made it a particularly informative laboratory for studying production networks, but its just-in-time requirements and supplier organisation were not universal. The broader Czech experience showed that different branches combine inherited skills, capital needs, labour requirements and exposure to international competition in different proportions.

A persistent concern was the possibility that internationally mobile production could leave as readily as it had arrived. In 2008, Jan Ženka investigated the risk of delocalisation among hundreds of foreign-owned manufacturing firms in Czechia. Rather than assuming that a foreign company was necessarily unstable, he examined factors that might make relocation easier or more difficult, including capital intensity and the complexity of production. Research with Vladislav Čadil published in 2009 extended this approach to technology-intensive manufacturing and its regional distribution. Their work questioned a potentially misleading classification: a firm operating in a high-technology branch need not perform particularly sophisticated functions at its Czech site. The durability of regional employment depended partly on what a plant actually did and how deeply its capabilities were rooted. This offered policymakers a better basis for judging investment quality than sector labels alone.

These findings exposed a tension within development policy. Regions needing jobs most urgently were sometimes encouraged to compete for investments whose main advantage was the availability of relatively inexpensive labour. Such projects could provide immediate relief yet be vulnerable when wages increased or another location offered lower costs. Conversely, firms requiring specialised expertise and expensive equipment might be more securely anchored but create fewer jobs for workers displaced from an older industry. No single investment criterion resolved this problem. An effective regional assessment had to ask how a proposed factory would use existing skills, what kinds of subcontracting it might generate and whether it offered realistic possibilities for learning. The central geographical challenge was to connect the immediate gains from employment to the longer development of a place’s productive capacities.

The global financial crisis of 2008–2009 supplied a severe test of the industrial networks established during the previous decade. Export-dependent automotive companies faced a sharp contraction in demand while attempting to preserve the relationships and capabilities on which recovery would depend. The effects on workers and supplier firms varied with their position in the value chain. Pavlínek and Ženka analysed changes in unemployment across Czech microregions and linked them to the structure of local automotive employment. Their 2010 study used firm-level indicators to examine vulnerability rather than infer it directly from the number of factories present. A subsequent investigation by Pavlínek followed the effects of the crisis in Czech and Slovak automotive enterprises, including changes in output, employment and plant operations. Both studies made clear that integration into international production brings exposure to disturbances transmitted through those same networks.

The crisis also revealed the limits of a narrow view of industrial competitiveness. A plant could have a modern production line and a productive workforce yet still lose shifts because its customers abroad reduced orders. Suppliers with little bargaining power were particularly

exposed to pressure on prices and delivery terms, even when they had already invested heavily in meeting quality standards. The shock therefore illuminated the difference between technical efficiency and control over demand. At the regional level, it mattered whether workers could move into alternative employment and whether an area's industrial base was concentrated in closely related activities. Resilience was not simply the ability of one large enterprise to resume production. It depended on the wider set of local opportunities, organisational relationships and capacities that allowed a region to absorb or adapt to external change.

The expanding network perspective did not erase older geographical explanations based on the character of industrial districts. Czech factories operated within regions possessing particular combinations of engineering skills, vocational education, research institutions, logistics facilities and business services. Those resources could help an investor launch production, and they could enable domestic enterprises to become suppliers. Yet their usefulness was not independent of corporate governance: a locally capable engineering team might have little influence if design remained centralised in a foreign headquarters. Work on automotive research and development illustrated this distinction. Pavlínek's 2012 investigation of the internationalisation of corporate research found that manufacturing growth in East-Central Europe had not been matched by a comparable relocation of the most strategic research functions. For Czech economic geography, the challenge became to explain both the strengths of the industrial workforce and the organisational boundaries placed upon it.

The term 'dependent growth' captured a substantial part of this experience without denying the achievements of industrial transformation. In his 2017 monograph, Pavlínek analysed the rapid expansion of the East-Central European automotive industry through foreign investment and the constraints created by its place within corporate production systems. Access to technology, capital and markets had transformed the sector and supported employment. At the same time, its dependence on externally controlled firms influenced the distribution of strategic activities, the terms offered to suppliers and the prospects for independent upgrading. The book placed Czech evidence within a wider Central European comparison, avoiding an interpretation based solely on national policy. It also explained why indicators that appear unequivocally positive at the country level can coexist with persistent questions about the future autonomy of enterprises and the developmental gains received by host regions.

The idea of an 'integrated periphery' further refined the spatial argument. Czech automotive production was not isolated from Europe's industrial core; it was deeply linked to it through investment, trade and tightly managed production systems. Integration had brought technical modernisation and substantial output, but corporate authority remained unevenly distributed across the network. Pavlínek's 2018 analysis of supplier relationships in integrated peripheries emphasised the importance of the quality, not merely the number, of local linkages. Although much of its empirical investigation concerned Slovakia, the conceptual questions also applied to Czech manufacturing. How far could suppliers develop independent competences? Which functions were retained close to corporate headquarters? Under what conditions could a production location gain more influence within an international network? These questions shifted the discussion from whether Czechia was industrially connected to Europe towards how that connection was organised and governed.

The regional consequences of multinational ownership were nonetheless too varied to support a simple opposition between foreign and domestic firms. Some foreign subsidiaries developed lasting relations with local training institutions, expanded technical departments and reinvested earnings. Others performed narrower tasks and relied more heavily on suppliers elsewhere. Domestic enterprises also differed greatly in their capacity to innovate, finance investment or enter demanding export markets. A geographical explanation therefore needed to consider ownership together with firm size, supplier tier, product complexity, location and time. Pavlínek's 2022 review of foreign investment in less developed regions returned to this point, arguing that the long-term developmental implications of investment require close attention to uneven power and territorial conditions. The Czech record furnished particularly rich evidence because it combined old industrial traditions with several decades of exposure to international capital.

The period after 2020 added new pressures to the production arrangements built since the 1990s. The COVID-19 pandemic disrupted factories and cross-border supply movements; shortages of particular components subsequently exposed the difficulty of coordinating highly specialised international inputs. These disturbances did not mean that global production networks had ceased to function. They showed instead that the efficiency of finely tuned supply relationships could coexist with vulnerability when one link failed. For Czech regions dependent on export manufacturing, interruptions in other countries could translate quickly into changed production schedules and uncertain employment at home. The geographical scale of risk therefore extended well beyond the district or state in which a factory operated. Research on regional economic resilience increasingly compared different kinds of shock and asked how industrial specialisation altered their effects.

A 2024 study by Jan Ženka, Jaroslav Rusnák and Adam Červenka provided an instructive example of this broader comparative direction. The authors examined Czech and Slovak regional resilience across four recessionary episodes, including the global financial crisis, the pandemic and disruptions associated with Russia's war against Ukraine. They distinguished the effects of automotive specialisation, business services and foundational economic activities while considering differences among old industrial and other regions. Their analysis found that patterns of resistance varied between crises; a structure that helped in one episode did not necessarily protect a region in another. This qualified the assumption that diversification or specialisation must always have the same consequence. By examining repeated shocks, the study connected the geographical effects of global production with a longer question concerning the capacities of regional economies to endure and recover.

The transition towards electric vehicles raised a different kind of challenge because it concerned the future content of production rather than simply the stability of existing orders. Automotive companies had to decide where to locate battery-related activities, new components, vehicle assembly and the technologies associated with electric propulsion. Regions deeply invested in internal-combustion production faced uncertainty about the future demand for particular skills and supplier products. Pavlínek's study published in Empirica in 2023 analysed the uneven transition of the East European automotive periphery and the leading role played by foreign manufacturers. It suggested that industrial change would be

shaped by decisions taken across the wider European production system rather than by the Czech market alone. The issue was not merely whether factories would manufacture electric cars, but which new functions and relationships the transition would create in their host regions.

These developments broadened the historical meaning of restructuring. In the 1990s it often appeared as the replacement of state-socialist production arrangements with private ownership and market-oriented management. In the 2000s it increasingly involved the formation of internationally coordinated supplier systems and the acquisition of new production competences. After the financial crisis, researchers paid closer attention to risk, power and the unequal capture of value. During the 2020s, technological transition, disruption and the future geography of manufacturing brought further uncertainty. The sequence was not a series of neatly separated stages: older industrial difficulties persisted alongside the growth of new sectors, and problems of ownership and governance remained relevant throughout. What changed was the range of evidence and concepts through which Czech economic geographers could interpret the same industrial landscape.

One major methodological advance was the combination of territorial statistics with information on individual enterprises. A map of employment concentrations could indicate where manufacturing mattered, but it could not by itself reveal whether a factory designed its products, bought locally or depended on a single foreign customer. Questionnaires, interviews with managers and suppliers, company accounts and evidence on ownership were therefore brought into dialogue with regional indicators. Studies of automotive upgrading, delocalisation and the effects of recession benefited especially from this mixed approach. It made possible the comparison of firms occupying different positions within one production network and the aggregation of their characteristics to regions. The empirical challenges remained substantial: company classifications change, confidential data limit what can be disclosed, and a local establishment does not always correspond neatly to an independent enterprise. A more detailed geography nonetheless emerged from the effort to connect organisational and territorial evidence.

By 2025, the research carried out in Czechia had given industrial geography a distinctive international contribution. The experience of restructuring an old manufacturing economy while incorporating it into European production systems offered an unusually revealing setting for testing ideas about foreign investment, upgrading, dependency and regional development. The most important conclusion was not that foreign capital had rescued Czech industry or that it had deprived it of independent prospects. Both propositions were too simple for the evidence. International investment could transform productive capacity, yet its regional value depended on the functions assigned to local plants, the strength of domestic suppliers and the distribution of decision-making authority. Industrial decline could remove employment without eliminating a region’s skills, just as industrial growth could increase exports without delivering equal benefits to every locality. Czech economic geography advanced by explaining those differences and by asking what they meant for the long-term prospects of industrial regions.

Innovation, Knowledge and Regional Development: Institutions, Enterprises and Territorial Competitiveness

A university laboratory and a nearby manufacturing plant may occupy the same urban district without exchanging more than occasional visitors. Conversely, a small engineering company can acquire the knowledge it needs from customers and suppliers scattered across several countries. This difference between the geographical proximity of expertise and the actual movement of knowledge became an increasingly important subject of Czech economic geography after 1993. Research on the post-socialist economy had initially concentrated on ownership, industrial decline, employment and the location of foreign investment. As the market economy matured, another question acquired equal force: under what conditions could Czech places generate, absorb and use new knowledge rather than merely accommodate production organised elsewhere? Between 1993 and 2025, the answer came to involve universities, enterprises, regional governments, innovation intermediaries and the relationships connecting them. It also required a more demanding conception of competitiveness, one that distinguished an increase in output from a lasting improvement in the capacity to innovate.

The independent Czech Republic inherited a considerable stock of technical education, industrial experience and scientific institutions. Engineering universities in Prague, Brno, Ostrava, Plzeň and Liberec had trained specialists for different branches of manufacturing, while the Academy of Sciences and university research departments sustained expertise in mathematics, physics, chemistry, materials and the life sciences. Yet these resources belonged to a system whose relationships with production were being reconstructed. Laboratories had often operated within sectoral research organisations or large enterprises; established channels of commissioning, financing and application were disrupted by privatisation and organisational change. Some research establishments adapted to competitive contracts and international cooperation, whereas others lost their former industrial partners. The economic-geographical issue was therefore not a simple shortage of educated people. It was the uneven capacity of regions and institutions to connect inherited knowledge with emerging markets, new firms and changing technological requirements.

Innovation was not treated simply as a synonym for scientific discovery. A firm could introduce a new production process, adapt machinery to a particular customer, redesign its logistics or offer an improved service without publishing a paper or obtaining a patent. In traditional manufacturing regions, such changes often depended on practical engineering skills and experience accumulated through work. Universities and research institutes were especially important for some sectors, including biotechnology, yet market knowledge and cooperation with clients could matter more immediately in others. The distinction raised methodological difficulties because indicators commonly used to describe innovation, such as research expenditure, patent applications and scientific publications, capture different activities. Pavla Žížalová and Pavel Csank raised these measurement problems in 2009 by examining the relationship between research indicators and uneven regional development. One of the distinctive contributions of Czech regional research was its insistence that a convincing

account of innovation required evidence about enterprises and their networks as well as statistics about scientific capacity.

The new regional self-government system created an institutional setting in which these questions could be addressed. Fourteen self-governing regions became operational at the beginning of 2001, and their responsibilities for regional development opened possibilities for strategic cooperation with universities and enterprises. European regional policy and the preparations for Czech accession to the European Union in 2004 provided additional models and resources. The transfer of a policy vocabulary from older European innovation regions, however, did not automatically establish functioning local partnerships. Regional authorities differed in financial capacity, administrative experience and the degree to which leading enterprises and research institutions were willing to cooperate. In some places a strategy began with an existing community of organisations; elsewhere the document came before the relationships it was supposed to organise. This variation supplied Czech geographers with an unusually revealing setting for examining the actual formation of regional innovation policy.

Jiří Blažek and David Uhlíř analysed these difficulties in their 2007 study of regional innovation policies and Prague. They reconstructed the conditions under which an innovation agenda appeared in the early 2000s, including administrative decentralisation, foreign investment in research-intensive activities and the growing influence of European approaches to regional development. Their case study of the capital's innovation strategy questioned whether an imported regional-policy model was being translated into an institutional setting capable of using it. Prague possessed exceptional universities, research organisations and professional services, but an abundance of knowledge-producing institutions did not ensure that they worked as a coherent regional system. The study helped shift attention from the formal adoption of policy instruments to the less visible processes through which cooperation and trust might be established. It also made policy transfer itself a subject of geographical enquiry.

A broader theoretical reconstruction accompanied this empirical research. Blažek and Uhlíř's successive editions of Teorie regionálního rozvoje, including the substantially revised edition of 2020, connected international debates about regional innovation systems, global production networks and evolutionary development to problems encountered in Czechia. Earlier approaches emphasising the relative attractiveness of locations remained useful but no longer explained why enterprises in apparently similar places differed in their access to knowledge. Institutional theories directed attention towards norms, networks and organisational capabilities; evolutionary perspectives emphasised inherited specialisations and the possibility of creating new economic paths. Such concepts were not an intellectual import detached from Czech evidence. Their value lay in making it possible to distinguish between a region rich in research establishments, a region with effective knowledge exchange and one able to use collaboration to create activities that had not previously existed there.

In a 2012 article in Geografie, Blažek placed regional innovation systems beside global production networks as two complementary approaches to contemporary competitiveness. The first concerned relationships among companies, universities and intermediary organisations within particular institutional settings. The second explained how firms' positions in wider production systems shaped their access to markets, technologies and

strategic decision-making. These perspectives were especially pertinent to a country where many internationally competitive factories were subsidiaries of foreign enterprises. A region might possess dense local relations but limited access to advanced international knowledge, or strong global connections but weak collaboration among organisations within its borders. The most significant question was how these spatial scales interacted. This argument also linked new research to the Czech geographical tradition at Albertov, while acknowledging the need to engage more fully with international regional studies.

The distinction among different knowledge bases gave this debate sharper empirical content. Analytical knowledge is particularly important where research seeks to explain processes or produce discoveries that can be codified, as in many activities in biotechnology. Synthetic knowledge is created through combining existing techniques, designing solutions and learning from production and users, as occurs frequently in engineering and software applications. Symbolic knowledge, relevant to cultural and creative activities, follows yet another logic. These categories describe dominant modes rather than rigid divisions between sectors or companies. They imply that a policy intended to build effective links between enterprises and knowledge institutions should not assume that all industries need the same type of laboratory, partner or intermediary. Geography matters because the availability and usefulness of knowledge depend on both its character and the relationships through which it circulates.

A revealing comparison was undertaken by Blažek, Pavla Žížalová, Petr Rumpel and Karel Skokan in their research on biotechnology in Prague and information and communication technologies in Ostrava, published in European Planning Studies in 2011. Rather than assume that knowledge-intensive industries would automatically depend on nearby universities, they investigated the location of different sources of technological and market knowledge. The results showed that patterns varied with knowledge bases and with the particular question being solved by an enterprise. Scientific knowledge, practical expertise, customers and information about markets could have different geographical ranges even within a single sector. For post-socialist regional studies, this was an important move beyond counting firms and research institutions. It showed that the economic meaning of a regional concentration could only be understood by tracing the connections that sustained its activity.

Prague represented both the most powerful concentration of knowledge resources and one of the clearest warnings against equating concentration with integration. The metropolitan area contains Charles University, the Czech Technical University, institutes of the Czech Academy of Sciences, specialist hospitals, research facilities and a dense market for advanced professional services. These assets attract skilled workers, national decision-making functions and foreign organisations seeking scientific or commercial partners. Yet each institution follows its own priorities, funding arrangements and career incentives. Research groups may maintain closer connections with foreign colleagues than with neighbouring companies, while locally based enterprises may obtain expertise through their parent organisations or customers abroad. A map displaying research establishments can therefore suggest a much more unified innovation system than exists in practice. Economic geography made this apparent contradiction into an empirical problem rather than treating metropolitan advantages as self-explanatory.

Blažek and Žížalová's 2010 study of biotechnology in the Prague metropolitan region demonstrated why such distinctions matter. Earlier accounts had described Prague as an innovation system with abundant institutions but weak cooperation between them. Their investigation found relatively intensive relationships within the emerging biotechnology sector, suggesting that the city could contain several partially distinct systems of knowledge exchange. Scientific specialisation, personal networks and the requirements of individual firms influenced which local links became significant. The findings cautioned against assigning an entire metropolis a single institutional character. A fragmented regional system in aggregate could contain effective, closely connected specialised groups. Conversely, a cluster visible in company listings could have weaker connections than its apparent density implied. Sectoral fieldwork thus changed the interpretation of a familiar metropolitan pattern.

The wider Prague–Central Bohemia area also illustrated the difficulty of matching functional research territories with administrative boundaries. An industrial or biomedical research site located beyond the capital's official border may draw its workforce, collaborators and financial resources from the metropolitan region. BIOCEV, the biotechnology and biomedicine research centre at Vestec, was approved in 2011 and completed in 2015 through cooperation between Charles University and institutes of the Academy of Sciences, with its research operation developing during the following years. Its location outside Prague's administrative territory did not make it independent of the capital's scientific institutions. For regional policy, the distinction was consequential: research programmes, European funding categories and statistical reporting could follow boundaries that knowledge exchange regularly crossed. The centre therefore belongs to the history of both scientific infrastructure and metropolitan regional development.

The long-term statistical record confirms the exceptional concentration of research activity. Czech Statistical Office figures for 2024 recorded approximately CZK 146.9 billion in total national research and development expenditure. Prague accounted for about CZK 60.2 billion, South Moravia for CZK 25.2 billion and Central Bohemia for CZK 18.4 billion. Taken together, these three regions represented well over two-thirds of the total. The amounts indicate where research was performed, however, not simply where its economic benefits accrued or where all decisions affecting it were made. Research undertaken in a capital-city headquarters may serve production throughout the country, and a factory in another region may use knowledge developed abroad. The unequal geography of expenditure is therefore an important starting point for analysis, but not a sufficient measure of the capacity of individual regions to convert scientific activity into economic development.

South Moravia became the most frequently cited Czech example of innovation policy emerging through sustained regional initiative. Brno's universities, technical traditions and research institutions supplied a significant stock of expertise, but the region also faced the problems associated with the restructuring of established industries. Regional leaders began to devise an innovation strategy in 2002, before the policy had become fully institutionalised at the national level. The new approach was influenced by international cooperation and by the wish to develop a practical connection between research capabilities and entrepreneurship. Its success depended not only on access to European ideas but on the willingness of local

authorities and universities to accept joint responsibilities. The case illustrates how a region's inherited difficulties can become an incentive to pursue a different developmental trajectory, provided that relevant organisations can agree on priorities and sustain them beyond a single project.

The South Moravian Innovation Centre, known as JIC, was founded in 2003 through cooperation among the South Moravian Region, the City of Brno and local universities. It developed services for emerging technology companies and gradually became a recognised intermediary between public authorities, researchers, entrepreneurs and investors. The importance of such an organisation cannot be reduced to the number of start-ups receiving office space or advice. An intermediary can help firms identify suitable expertise, interpret unfamiliar funding requirements, recruit experienced personnel and encounter potential collaborators whom they would otherwise be unlikely to approach. It also accumulates knowledge about regional companies and their changing requirements. In this respect, the JIC model showed how organisational capacity could become a regional asset. What began as a response to the absence of an effective innovation-support infrastructure developed into a continuing system of relationships and services.

The regional innovation strategy in South Moravia was also notable for its successive revisions. A strategy written once is a statement of aspirations; a strategy revisited in the light of company experience and institutional performance can become a means of collective learning. Business incubation, support for international expansion, contacts with research teams and the cultivation of entrepreneurial networks required different arrangements as the regional economy changed. The emergence of companies such as Y Soft and Flowmon, both associated with the region's entrepreneurial environment, made the growth of locally founded technology enterprises visible. Yet the value of these examples lies less in providing a universally replicable story of success than in revealing the long duration of institutional development. Competent people, patient regional funding and repeated engagement between actors helped make specialised support reliable enough for companies to use it.

Scientific infrastructure added another dimension to South Moravia's innovation landscape. The Central European Institute of Technology, CEITEC, was approved for substantial European support in 2011 and brought together research in life sciences, advanced materials and related technologies within a Brno-based institutional consortium. New laboratories and equipment could broaden the range of problems addressed by regional researchers and make the area more attractive to international collaborators. Such a centre was not simply an addition to the region's commercial infrastructure. Its direct purpose was scientific excellence, yet training, equipment access, joint research and the formation of new ventures could create wider connections over time. Geography was involved at every stage, from the location of sophisticated facilities and research employment to the mobility of scientists and the reach of possible industrial partnerships. The establishment of a scientific centre and the creation of an effective commercial innovation network remained related but distinct achievements.

A comparative study by Blažek, Žížalová, Rumpel, Skokan and Petr Chládek, published in 2013, investigated innovation strategies in Prague, South Moravia and Moravia-Silesia. The researchers found significant differences in policy design and implementation that could not

be explained by the amount of research infrastructure alone. They drew attention to the interaction between knowledge-producing organisations, competent intermediaries and consistent support from regional political leaders. The comparative design was important because it replaced a simple list of examples with a question about why similar policy intentions led to different outcomes. It also demonstrated that the formation of innovation systems was a historical process. Earlier industrial structures and university traditions mattered, but institutional initiative and the capacity to organise cooperation could redirect the use of those inherited resources.

Moravia-Silesia offered an especially demanding environment for this redirection. In Ostrava, coal extraction, metallurgy and heavy engineering had shaped employment, professional education and urban infrastructure. Their restructuring left environmental burdens and a public image associated with declining heavy industry. Yet the region also possessed technical universities, engineering skills and enterprises capable of developing knowledge-intensive activities. The growth of information technology and specialist services could use elements of this inheritance while requiring new professional networks and markets. The critical question was whether emerging industries would form a diversified economy and generate local decision-making functions, or remain small activities within an industrial system still dependent on external corporate strategies. Regional innovation policy had to deal simultaneously with old assets, new firms and the social consequences of economic transition.

Large research facilities altered the possibilities available to the Ostrava region. The IT4Innovations National Supercomputing Center arose from a project approved for European funding in 2011, led by VSB–Technical University of Ostrava with several academic partners. High-performance computing has uses in engineering design, materials modelling, environmental analysis and many other fields, and its presence can expand the range of research partnerships available to a region. The geographical consequences depend, nevertheless, on access and use rather than on the physical existence of equipment. Researchers and firms must be able to formulate problems that benefit from the technology, obtain time and expertise to employ it, and turn results into further work. Ostrava's case therefore made the idea of an innovation infrastructure more demanding: a major facility can provide an opportunity for regional learning, but further organisations and competencies are needed to convert that opportunity into broad economic effects.

Innovation-related research was not confined to the Prague, Brno and Ostrava metropolitan areas. Plzeň's technical institutions, Liberec's engineering traditions, research associated with Olomouc and Zlín, and the scientific establishments of South Bohemia provided different combinations of skills and specialisation. The locations of automotive development, precision engineering, materials research, biotechnology and information services often reflected capabilities accumulated long before the latest innovation strategy. Yet the capacity to sustain business-oriented research partnerships differed considerably among them. A smaller university city could create specialised international connections while lacking the broad labour market of a metropolis. An advanced factory could undertake substantial experimental development without a nearby comprehensive university. Comparing these places required

attention to the particular knowledge base and the institutional relationships of each activity rather than the mechanical application of a metropolitan model.

Milan Viturka's research at Masaryk University provided a complementary approach to territorial competitiveness. His 2007 analysis combined indicators of the business environment, utilisation of human resources and innovative potential, and applied the framework to Czech regions. The 2010 study in Geografie elaborated an approach to regional disparities with observations at the scale of more than two hundred micro-regions, subsequently aggregated to the fourteen self-governing regions. These studies were not detailed accounts of individual innovation networks; their strength lay in establishing a territorial framework in which economic conditions and the capacity for innovation could be considered together. A region's performance depended on infrastructure, employment conditions, existing enterprises and human capital as well as formal research activity. Such work supplied policymakers with a way to compare territorial prospects while also exposing the limits of any single indicator of competitiveness.

The growing importance of knowledge-intensive business services further complicated the map of regional development. Consulting, software, engineering design, specialised financial services and professional advice can support innovation in manufacturing without themselves producing a tangible industrial product. In their 2017 study, Ženka, Josef Novotný, Ondřej Slach and Igor Ivan examined the spatial distribution of such services in Czechia. Their findings underlined the importance of the urban hierarchy and showed that a country's manufacturing research activities need not have the same spatial distribution as its advanced business services. Some forms of knowledge-intensive service were concentrated in major cities, while particular industrial towns could support specialised functions. This mismatch created opportunities and difficulties for companies outside metropolitan areas: a manufacturer might possess substantial technical capability yet depend on distant providers for other parts of its innovation process.

National institutions shaped the opportunities available to all these regions. The Technology Centre Prague, founded in 1994 as the Technology Centre of the Academy of Sciences, became an important organisation for international research cooperation, technological transfer and research-policy analysis. It helped connect Czech researchers and firms with European programmes and supplied strategic studies to decision-makers. Its work shows that intermediary institutions need not be purely regional to influence regional innovation. A nationally based organisation can make international information accessible to researchers working in many locations, even if opportunities for using that information remain territorially uneven. The institutional history also illustrates the gradual development of a policy expertise specialised in research collaboration rather than in the direct administration of industrial investment.

A further institutional change was the establishment in 2009 of the Technology Agency of the Czech Republic, responsible for supporting applied research, experimental development and innovation. Its programmes offered a national framework for competitive project support and cooperation between research organisations and enterprises. The agency's significance for economic geography lay partly in its influence on the location and character of collaborative

projects. A publicly supported partnership could bring together a university and a company in the same city, or organisations based in different regions whose expertise complemented one another. Funding could help overcome the initial costs of cooperation, though it could not ensure that results would subsequently be used commercially. Regional comparisons therefore required attention not only to the distribution of grants but also to the type of collaboration, the capacities of participants and the activities that continued after a project ended.

European Structural Funds financed an especially visible transformation of the national research landscape. The Operational Programme Research and Development for Innovations for 2007–2013 supported the establishment of eight centres of excellence and forty regional research centres, with implementation extending beyond the formal programming years. Advanced infrastructure became available in locations that had previously lacked comparable facilities. Because of the programme's territorial eligibility rules, the expansion also reflected the distinction between Prague and areas outside the capital. New buildings and equipment could improve research performance, enable the recruitment of specialists and support technology transfer, but they introduced continuing requirements for maintenance, staff and future funding. The programme thus made research infrastructure a major issue of territorial development policy and created a long-term test of whether capital investment could stimulate durable networks of innovation.

Researchers increasingly recognised that the acquisition of expensive equipment was only one stage in building an innovation environment. An advanced laboratory must attract competent scientific teams, maintain international credibility and identify organisations capable of using its knowledge. Companies may need assistance in expressing technical problems in terms suitable for joint research, while academics operate within evaluation systems that reward achievements not always aligned with commercial timetables. Intellectual property rules, contractual responsibilities and differences in professional language can obstruct promising partnerships. These obstacles are particularly significant in regions where companies have limited experience of research collaboration. Measuring the effects of a newly built centre therefore requires a longer horizon than the completion of construction or the first reporting cycle. The historical meaning of the Czech infrastructure investment lies in the institutional relationships it enabled as much as in the facilities themselves.

The 2014 adoption of a national research and innovation strategy for smart specialisation introduced a more explicit relationship between innovation policy, territorial strengths and European funding requirements. Rather than support every promising sector in the same way, the approach sought areas in which existing capabilities could provide foundations for further development. The strategy connected national priorities with regional assessments and with processes intended to involve companies, universities and public authorities in defining opportunities. Its later 2021–2027 version, approved in January 2021, placed a knowledge-based and more resilient economy at the centre of the policy vision. This progression reflected a change from the early effort to establish innovation-support institutions to an attempt to coordinate priorities across sectors and administrative levels. The effectiveness of the

approach still depended on the quality of the information and participation through which specialisation was selected.

Smart specialisation was sometimes misunderstood as the designation of an official list of technologies or industries. Its more demanding element was the continuing identification of opportunities through an entrepreneurial discovery process. Established enterprises could reveal markets and technical bottlenecks, young companies could suggest unfamiliar applications, while researchers contributed knowledge that might not yet have an obvious commercial use. Regional authorities and intermediaries were expected to bring these perspectives together, revise choices and assess progress. In practice, organisations differ in their ability to participate, and consultation can become a procedural exercise when decisions have already been made. Comparative research on Central and Eastern Europe, including South Moravia, showed the importance of keeping stakeholders engaged during implementation as well as drafting. The policy question was not whether a region had produced a strategy, but whether it had developed the capacity to learn from and change that strategy.

Enterprise–university relations supplied a particularly revealing test of this capacity. Vojtěch Kadlec and Blažek's 2015 investigation compared the perceptions of leading life-science academics in Prague and South Moravia. The researchers found meaningful differences in the obstacles reported by academics seeking collaboration with companies. In South Moravia, a more developed regional innovation strategy appeared to have helped create conditions in which basic barriers to forming cooperation were less dominant, even though challenges to expanding partnerships remained. Prague's substantial scientific endowment did not necessarily produce the same experience of institutional support. The finding was not that all Brno laboratories cooperated successfully or that Prague lacked effective partnerships. It was that regional governance and intermediary arrangements could change how researchers experienced the possibility of collaborating with firms, even within the same broad scientific field.

Evaluating financial support raised similar issues of context. In a 2018 study published in Applied Geography, Viktor Květoň and Petr Horák examined the effects of public research and development subsidies on Czech firms between 2007 and 2014. Their comparisons suggested that the net effects varied by region and industry, with stronger effects of direct support in some medium-developed and less research-intensive settings than in the most advanced regional systems. The findings questioned the assumption that the regions already possessing the largest scientific capacities would necessarily receive the greatest marginal benefit from each additional subsidy. They also underlined the importance of distinguishing direct grants from indirect instruments such as tax support. Public expenditure could facilitate activity that otherwise would not take place, but a positive result depended on firm capabilities, the type of support and the economic conditions in which it was delivered.

A later analysis by Adam Janošec, Gabriela Chmelíková, Ivana Blažková and Kristina Somerlíková examined differences between structurally affected and other Czech regions over 2012–2022. Published in 2024, the study considered the relationship between public support for research and development and several measures of the regional innovation environment. Its results suggested that the relative response to support could be substantial where existing

research resources were limited. The finding should not be confused with proof that a given subsidy caused every subsequent improvement, since regional changes reflect multiple influences. Nevertheless, it strengthened an important policy question: should scarce public resources concentrate on established centres of excellence, support weaker regions attempting to develop new capacities, or pursue different objectives through different instruments? The geographical distribution of research funding was revealed as a problem of institutional development as well as of efficiency.

The character of knowledge itself also became a more explicit subject of international comparison. Květoň and Kadlec's 2018 study of European regions examined the evolution of knowledge bases and their connections with innovation performance. Its conceptual framework offered Czech researchers a way to investigate whether different combinations of analytical, synthetic and other knowledge resources supported different forms of development. Regional diversification is rarely created from nothing: new activities often draw on some existing professional capabilities, even when their commercial applications are unfamiliar. Yet excessive reliance on a narrow set of related industries can restrict opportunities when technology or demand changes. The evolutionary approach therefore treats the productive history of a region as both a resource and a possible constraint. Its policy implication is to search for credible routes into new activities instead of assuming that every territory can imitate the same high-technology specialisation.

The position of enterprises in international production networks posed another challenge to purely local accounts of innovation. A Czech company can collaborate intensively with foreign customers and supply a technologically advanced component, while participating only marginally in the innovation activities of nearby firms or universities. Alternatively, a locally oriented company may possess a dense network of domestic collaborators but few routes into global technological markets. Květoň and Horák's 2024 study of firms in four Czech regions examined the interaction between vertical supply-chain integration and horizontal research and development collaboration. It showed that internationally connected, technologically sophisticated enterprises were not necessarily the most deeply embedded in regional research networks. The authors also found that intensive research collaboration was associated with greater resistance to shocks, while some technologically capable firms with few collaborations could face longer-term vulnerability. The findings give a practical meaning to the relationship between connectivity and resilience.

The green transformation brought innovation policy into closer contact with inherited industrial specialisations by the early 2020s. Changes in energy systems, materials, mobility and environmental regulation affected the future markets of engineering firms and suppliers across Czechia. Established manufacturing regions possessed skills that might be adapted to new technologies, but some existing assets could lose value as product requirements changed. Regional strategies consequently faced questions about the direction of innovation rather than its quantity alone. The goal might be to strengthen existing industrial capabilities, diversify into related fields or develop entirely new relationships among firms and research organisations. A geographically grounded policy needed to distinguish these possibilities, assess the social

costs of transition and consider how public institutions could support learning without claiming to predict which enterprises would succeed.

Building on their earlier work on agency in old industrial regions, Blažek and Květoň's 2025 analysis of regional governance and system-level agency offered a further step in this direction. They argued that the possibilities for developing new industrial paths depend on the interaction between organisational initiative, regional assets and the manner in which an innovation system is governed. They proposed typology distinguishing governance arrangements by administrative strength and institutional inclusiveness. This made a crucial historical point: regional development does not follow mechanically from the initial stock of factories, universities or skilled workers. Institutions and actors can combine assets in new ways, but their capacity to do so is uneven and cannot be inferred simply from a region's wealth. The research also clarified why strategies based on identical terminology may deliver very different opportunities for economic renewal.

The most difficult question remained the relationship between regional innovation and regional inequality. Concentrating research infrastructure in well-established academic centres may generate scientific excellence and international visibility. Dispersing resources more widely may help develop skills and partnerships in places that have previously received little attention. Neither objective can be pursued without costs, and the same policy instrument need not serve them equally well. The comparison between Prague, South Moravia, the industrial regions and smaller research centres showed that different types of institutional weakness require different responses. Where scientific capacity is strong but collaboration is limited, improved relationships may matter more than another building. Where enterprises have little absorptive capacity, supporting practical training and the first stages of cooperation may be more effective than attempting to establish an internationally prominent research cluster immediately.

Such methods also made assessment of public programmes less straightforward but more useful. The number of successful grant applications, new start-ups or patents is comparatively easy to report; the additional activity generated by a policy is harder to identify. Enterprises that receive support may already be more capable than those that do not, and the effects of a university collaboration may emerge long after its formal completion. Economic circumstances also alter outcomes: a programme introduced during a recession may appear different from one operating in a period of expanding demand. Counterfactual comparisons, sectoral controls and qualitative investigation of partnership histories help address these problems, though none removes all uncertainty. The strongest Czech studies therefore treated policy evaluation as an enquiry into mechanisms and contexts, not a mechanical judgement based on a single performance ranking.

By 2025, Czech economic geography had developed a substantial body of evidence about the changing relationship between knowledge and territory. Researchers had demonstrated that a research-rich metropolis may contain fragmented networks, that an industrial region can draw on international expertise without first becoming a miniature capital, and that long-term institutional cooperation can make a difference to the use of scientific capacity. Studies of firms showed why advanced production and strong local knowledge connections do not

necessarily coincide. The European Commission's 2025 Regional Innovation Scoreboard classified Prague as a Strong Innovator while revealing weaker performance in other Czech regions. Regional policy had meanwhile moved from early experiments in innovation strategies to a more systematic, though still uneven, framework of specialised institutions and smart-specialisation priorities. These developments did not eliminate territorial disparities or guarantee that every promising scientific result would become a successful enterprise. They did, however, make it possible to explain more precisely why knowledge contributes to development in some places and remains a largely unrealised resource in others.

The central lesson of the period was that competitiveness is produced through relationships sustained over time. Universities provide education and research, companies discover commercial problems and possibilities, public authorities establish conditions for cooperation, and intermediaries help knowledge cross organisational boundaries. Their activities take place in particular cities and regions, yet they are also connected to national funding systems, European research programmes and worldwide production networks. A region's future therefore cannot be read from the number of laboratories on its map, its industrial inheritance or its position in a statistical league table. It depends on how these resources are combined, who can act upon them and whether institutions retain the capacity to revise their choices. The Czech experience between 1993 and 2025 made innovation a central concern of regional development not by treating geography as an obstacle to knowledge, but by showing why the geography of knowledge continues to matter.

The Changing Geography of Agriculture, Transport, Services and Tourism

The changing Czech countryside, the new distribution centre beside a motorway and the crowded streets of Prague belong to a single geographical history. Each marks a different way in which economic activity found new locations after the dissolution of Czechoslovakia. Agriculture remained closely tied to soil, relief and inherited property relations, although its markets and incentives changed. Transport reorganised the practical distances between settlements and enlarged the territory within reach of a factory, a workplace or a shopping centre. Services moved both into highly visible suburban premises and into networks that could scarcely be mapped from the street. Tourism converted selected landscapes and historic towns into places of international consumption. For Czech economic geography, the challenge after 1993 was to trace these changes without assuming that the same market forces produced the same outcome everywhere.

The republic entered independence with a dense settlement network, a substantial industrial base, numerous small municipalities and transport routes inherited from several political economies. The transformation had begun before 1993, but independence and subsequent European integration supplied new institutional settings in which its territorial effects could be studied. Land restitution and the restructuring of farms occurred alongside the privatisation of retail, changes in public transport finance, the renewal of municipal government and the opening of borders to visitors. These processes altered how people travelled to work, where

they obtained everyday necessities and which localities could earn income from their surroundings. Geographers increasingly examined connections between sectors rather than treating agricultural, transport, service and tourism maps as unrelated inventories. A farm could depend on access to a wholesale market, a village shop on the frequency of bus services and a mountain destination on the environmental effects of visitors arriving by car.

Agriculture offered a particularly clear test of the relationship between institutional change and geographical continuity. Czech fields and pastures had long reflected the large-scale consolidation of production undertaken under state socialism, yet their use was also conditioned by differences between fertile lowlands and less productive uplands. The transformation of collective and state farms involved restitution claims, new ownership arrangements, leasing and the creation or reorganisation of enterprises. It did not restore the predominantly small-farm landscape that had existed before collectivisation. Large agricultural companies remained important, sometimes operating land owned by numerous different proprietors. This combination of fragmented ownership and relatively concentrated operational control became a defining feature of the Czech agricultural system. To map the sector simply by the number of farms would therefore misrepresent its territorial organisation. The area cultivated, the type of holding and the control exercised over land needed to be distinguished.

Ivan Bičík and Vít Jančák made this discrepancy central to the geographical interpretation of farming after 1990. Their study of Czech agriculture, published in Geografie in 2001, examined transformation as a process affecting land, labour, agricultural production and the structure of enterprises. It placed changing farm organisation within the geographical contrasts of the republic instead of treating reform as a uniform national sequence. The decline in agricultural employment could not be understood independently of alternative jobs available in nearby towns, while changes in crop or livestock production were connected to inherited equipment, soil conditions and market access. Their subsequent book on transformation processes in Czech agriculture provided a more extensive account of the first post-socialist period. The studies were important for their refusal to equate a legal change in ownership with an immediate change in landscape. Economic restructuring could happen relatively quickly; the material consequences on fields, farm buildings and rural employment unfolded over much longer intervals.

The geographical record of land use offered another means of detecting these delayed consequences. At Charles University, researchers associated with the long-running Land Use/Land Cover Changes in Czechia project combined historical cadastral statistics with maps and more recent observations. Bičík, Lucie Kupková, Leoš Jeleček, Jan Kabrda and colleagues demonstrated that expansion of built-up land, conversion of arable fields to grassland and afforestation were not interchangeable expressions of a single trend. They occurred in different settings and answered to different economic or environmental pressures. The 2015 collective monograph on land-use change from 1845 to 2010 placed the post-1990 decades within a longer history of intensification, retreat and landscape transformation. That perspective exposed a geographical paradox: the economic importance of farming fell, but decisions about agricultural land continued to shape a very large share of the country’s

physical surface. Land-use history consequently became part of economic geography rather than merely a branch of descriptive landscape study.

In the productive lowlands of the Elbe basin, central Bohemia and southern Moravia, arable farming remained closely associated with favourable growing conditions and commercial crop production. Other regions had more extensive grasslands, livestock holdings and mixtures of agricultural and forest use. Differences in rainfall, elevation and slope affected possible forms of production, but they were mediated by subsidies, machinery, access to processors and the organisation of agricultural enterprises. Jan Kabrda and Jančák examined how political and institutional measures influenced the agricultural landscape, while Ondřej Konečný later analysed spatial polarisation during the period of accession to the European Union. These enquiries shifted attention from a simple division between successful and unsuccessful farms towards the territorial distribution of different agricultural strategies. Commercial intensification in one district could coexist with environmental management or extensive grazing in another. The geography of farming became more differentiated in purpose, not merely in its overall economic performance.

European Union accession in 2004 changed the financial and regulatory setting for rural land management. The Common Agricultural Policy, rural-development programmes and agri-environmental measures offered payments linked to land area, production conditions and specified management practices. For regions with difficult terrain, these arrangements affected the feasibility of continuing agriculture and the economic incentives for retaining grassland. In favourable lowland areas they interacted with competitive production and the capacity of large operators to draw on investment and administrative expertise. Geographical analysis had to separate the intended effect of a measure from its actual territorial distribution. A payment available nationally might be taken up differently because of farm size, ecological conditions or the ability of an enterprise to negotiate its requirements. Maps of support could therefore reveal as much about institutional access and agricultural organisation as about the physical landscape. This represented an important extension of earlier work on agricultural production zones.

Organic agriculture provides a strong illustration. Jiří Hrabák and Lukáš Zagata, studying the sector’s development and regional differentiation, found that organic farming was concentrated especially in upland and mountain districts with less favourable conditions for conventional intensive agriculture. Their 2020 article did not interpret that distribution as proof of greater environmental awareness in all upland communities. Instead, it investigated the spatial diffusion of a production system shaped by natural constraints, policy incentives and the decisions of enterprises. At the land-block scale, the pattern was considerably more heterogeneous than a regional map might suggest. Organic grassland dominated many peripheral localities, whereas conversion of productive arable land presented a different economic calculation. The research illustrated why the interpretation of a seemingly straightforward indicator, such as the proportion of organically managed land, requires attention to how it is measured, the agricultural activities it represents and the purposes served by its geographical concentration.

Other researchers moved closer to the farmer's decisions. In a 2021 article, Tomáš Zavadil and Jančák used interviews to investigate how farmers' motives influence landscape structure. Their approach supplied evidence that could not be obtained from a land-cover map alone. Holdings making apparently similar use of soil might differ in their commitment to particular production methods, their relation to local employment or their reasons for retaining particular fields. The researchers' later work on agricultural employment examined the place of family farms in rural labour markets. Such holdings did not necessarily employ many people outside the family, yet agricultural work could still matter through its proximity to home, seasonal flexibility and relation to the continuity of village life. These studies corrected the tendency to judge rural agriculture only by its share of total employment. They connected farm economics to the everyday functioning of settlements without romanticising the capacity of small enterprises to reverse rural decline.

The official statistics underline the durability of the large-holding structure. The Czech Statistical Office's Integrated Farm Survey for 2023 recorded 33,166 agricultural holdings and an average operated area of approximately 106 hectares. Relative to the 2000 agricultural census, the number of holdings had declined, whereas their average size had risen; agricultural labour had fallen considerably. These figures do not by themselves describe the distribution of ownership or the diversity of farms. A legal entity managing extensive leased land and a family holding can be counted as two enterprises although their relations to surrounding settlements are very different. Nor is a national mean a reliable description of farms in individual districts. The value of the survey for economic geography lies in the possibility of connecting structural statistics with location, production type and the circumstances of rural labour markets. It shows how a sector of relatively modest employment continues to organise large territories and substantial capital assets.

The unused agricultural premises left by restructuring introduced another dimension. Buildings designed for the scale and technology of socialist collective farming were not automatically suited to the operations that succeeded them. Some remained in use, others became derelict, and still others found functions in storage, small manufacturing, housing or non-agricultural services. Josef Navrátil, Stanislav Martinát and colleagues examined former agricultural premises in four South Bohemian rural regions by comparing their use in 1989, 2004 and 2017. The study revealed movement in both directions: agricultural brownfields emerged after the first transition, but part of the stock was subsequently reused. This was evidence that rural transformation was not a single episode of abandonment. Adaptation depended on local markets, property arrangements, the physical condition of buildings and the ability of communities and investors to see a future use. Agricultural geography thereby intersected with research on brownfields, rural entrepreneurship and local planning.

Agriculture's broader geographical significance also appeared in the rise of multifunctional rural development. Food production could coexist with landscape maintenance, renewable-energy projects, farm accommodation and small-scale processing. Such combinations were unevenly distributed. A farm near Prague might serve a direct consumer market, while an upland holding could derive greater significance from grazing, environmental payments or visitors attracted by the landscape. In southern Moravia, vineyards were simultaneously

agricultural production sites and part of a regional tourism economy. These changes did not erase the difference between commercial and non-commercial uses of the countryside. Rather, they made the same parcel of land relevant to several forms of valuation. Geographers increasingly asked whose interests were served, how costs and income were distributed and whether diversification produced lasting local capacity. By 2025, the Czech countryside could no longer be described adequately through agricultural yields and the proportion of rural workers alone.

Transport changed the scale at which these rural and urban economies operated. Inherited railways, roads and settlement hierarchies had been formed over generations, but the geographical meaning of a connection depends on the services it carries and the destinations it permits people to reach. After 1993 the growing ownership of private cars, rising road freight, European integration and investment in strategic corridors affected both transport demand and accessibility. In the early transition, the private car offered many households greater freedom from scheduled services, while peripheral settlements still relied on buses and regional trains. A new motorway section could shorten a journey between cities without making a village nearby easier to reach on public transport. The resulting map of mobility was therefore more complex than the map of roads. Czech transport geography developed methods to compare these differences and to assess their consequences for regional development.

Road construction gave particular importance to the axes connecting Prague with Brno, Plzeň and the international border crossings. Industrial and logistics investment followed some of these routes, strengthening opportunities along motorway interchanges and in well-connected hinterlands. Yet transport-led development did not spread automatically from an upgraded road to all surrounding communities. Sites suitable for warehouses required substantial land, labour supply, vehicle access and planning permission, while localities bypassed by major investments might experience little benefit. The growth of road transport also created pressure through noise, emissions, traffic and land consumption. Freight movement became linked to the structure of industrial production discussed in the preceding chapter, but its spatial effects extended further, influencing retail supply chains, farm deliveries and tourism. An express route could promote economic integration over long distances while intensifying environmental burdens at particular junctions, town approaches and border corridors.

The transport statistics make the modal shift visible without reducing it to a story of absolute railway decline. Official series show a strong long-term expansion of passenger travel by private car, accompanied by rising demands on road space. Railway passenger transport followed a different trajectory: a contraction in the early transition, later recovery in important corridors and renewed interest in modernised long-distance services. Regional trains and buses, meanwhile, remained indispensable for residents without reliable access to a car. In 2024 Czech rail transport carried nearly 192 million passengers and public bus services carried approximately 345 million, according to the Czech Statistical Office’s data compiled from transport statistics. Neither figure says how easily a resident can reach a doctor or a secondary school. National passenger totals count usage, not unmet need; the routes between smaller places and the hours at which services operate are equally consequential. This distinction

helped transform transport geography from an account of network capacity into a study of opportunities.

Miroslav Marada and Viktor Květoň made that distinction explicit in their 2010 analysis of municipalities and socio-geographical micro-regions. They compared the supply of bus and train connections with household access to cars, using spatial statistics and regional typologies to explore unevenness. Their results suggested that differences in public transport supply were more pronounced than differences in household motorisation. The authors identified several distinct types of micro-regions rather than treating all rural places as alike. A municipality's proximity to a large centre, its position in a settlement hierarchy and the surrounding pattern of destinations influenced the options available to inhabitants. Their contribution was methodological as well as empirical. It demonstrated that accessibility should be mapped through combinations of modes and local characteristics. A settlement that appeared close to a city in straight-line distance could remain disadvantaged when connections were infrequent, indirect or poorly timed.

Research on individual localities extended this insight to the daily timetable. Květoň, Jakub Chmelík, Petra Vondráčková and Marada investigated public transport serviceability in the Sedlčany and Ledeč nad Sázavou micro-regions between 2001 and 2009. The two peripheral areas differed in their settlement patterns, but buses formed the backbone of public transport in both. Railway lines were important along selected routes without providing a general solution for dispersed villages. The study showed how fragmentation of settlement complicated the provision of services and made it costly to maintain the same frequency across every locality. For households, the relevant question was not whether a bus route existed on a map but whether it enabled a journey to work, school or a public office and a return at a reasonable hour. Such studies supplied a more demanding standard for discussions of territorial cohesion: accessibility had to be examined at the scale of the trip actually made.

The organisation of transport became more regionalised as authorities developed integrated public transport systems and coordinated services across operators. In urban regions, combinations of suburban rail, trams, buses and common ticketing allowed daily movements to extend across municipal boundaries. In more sparsely settled territories, coordination could improve transfers and reduce duplication but did not abolish the difficulties of serving small populations. Private operators and regional contracting altered the institutional landscape, while the management of rail infrastructure and passenger services acquired distinct responsibilities. The geographical effect of these reforms depended on how institutions translated a service obligation into timetables and connections. A regional boundary could be almost invisible to a passenger where fares and schedules were integrated, yet it could still create friction where services or planning priorities were poorly aligned. Institutional geography therefore became part of transport geography rather than an external administrative detail.

Railway modernisation raised questions about who would benefit from speed. Improvements on principal routes could strengthen Prague's connections to Brno, Ostrava, Vienna and other European centres. They also posed the problem of smaller towns: a faster intercity train might bypass a station or require a transfer, while regional services could become more valuable if they connected efficiently to the improved network. Daniel Seidenglanz placed Czech railway

developments in the context of European transport policy and competition among modes, stressing the relationship between infrastructure, institutional arrangements and market demand. More recent analyses considered the prospective geography of high-speed rail rather than assuming that its benefits would be automatic. The spatial distribution of travel-time savings and the position of stations emerged as matters of regional policy. Increased connectivity at national scale could coexist with stronger concentration of activity around a limited number of urban nodes.

Jakub Randák, Marada and Miroslav Vrtiška's 2021 study of possible high-speed rail alignments between Prague and Brno illustrated this more exacting approach. Their models examined changes in potential accessibility across Czech municipalities under different routing scenarios. The exercise did not claim that a proposed line had already been built; it tested how alternative alignments could redistribute access to opportunities. The distinction matters for a historical account ending in 2025, when much high-speed planning remained prospective. In geographical analysis, prospective infrastructure can be evaluated without converting a policy ambition into an accomplished development. The methods also helped reveal the different scales at which transport benefits appear: a corridor can improve movement between large cities while changing local accessibility only where feeder services, stations and surrounding settlement patterns make the connection usable. GIS modelling thus became a bridge between transport planning and territorial assessment.

Transport was inseparable from tourism as well as commuting and freight. Mountain resorts in the Krkonoše and Šumava, historic towns and spa centres depended on the ways visitors could arrive and move within destinations. Private cars helped make weekend journeys convenient but could overload roads and car parks in environmentally sensitive areas. Railways retained importance for particular towns and scenic areas, although station locations and onward connections affected their usefulness. Daniel Seidenglanz's work on rail transport and tourism development drew attention to the older role of railways in opening destinations to visitors and to the changing demands of contemporary tourism. A new transport route could enlarge a destination's market; it could also direct visitors towards a narrow set of sites, leaving neighbouring settlements with fewer gains. This made the transport system a factor in the geographical distribution of tourist income and environmental pressure.

By the end of the period, transport geography also had to account for decarbonisation, electrification and the resilience of networks. The economic consequences of climate-related disruptions, road congestion or interrupted rail links did not fall evenly on places. A business dependent on frequent deliveries faced a different vulnerability from a village whose last evening bus provided access to work. The distinction between transport volume and transport serviceability remained essential. Digital timetables and journey planners made services more visible, but better information could not substitute for a missing connection. The longer research trajectory from road and railway inventories to local accessibility models showed how closely transport had become connected to the study of opportunity and exclusion. It also prepared the ground for later work in which regional accessibility could be evaluated as a component of competitiveness rather than an exclusively engineering problem.

The geographical transformation of services was no less extensive, although it often left fewer permanent marks on land use than new transport infrastructure. In the early 1990s the distribution of shops, banks, restaurants and many personal services had to adjust to the end of central allocation, the restoration of private enterprise and the changing purchasing power of households. Small independent businesses emerged, but the arrival of foreign retail chains and new commercial property developers soon created powerful competitors. The transition was neither a simple replacement of public provision by private enterprise nor a uniform movement towards large cities. Its effects depended on income, motorisation, the inherited street network, commercial rents and the size of nearby consumer markets. Town centres, housing estates, suburban junctions and rural villages were differently placed to respond. For geographers, services became a means of observing daily movements and the changing hierarchy of settlements.

The first wave of large-format retail expanded shopping opportunities at the edges of major Czech cities, where developers could secure sufficiently large sites and provide extensive car parking. Hypermarkets, shopping centres and specialised outlets attracted journeys from surrounding municipalities and brought commercial functions into areas once treated mainly as urban fringe or industrial land. Josef Kunc, Petr Tonev, Bohumil Frantál and Zdeněk Szczyrba examined how shopping behaviour and retail attraction reorganised the Brno urban region. Their 2012 study related retail gravity and household choices to patterns of daily mobility. It showed why a shopping centre should not be regarded merely as a collection of shops. Customers combined purchases with employment, school and other activities, creating routes that reflected the wider structure of the metropolitan area. Such research gave new empirical content to the older geographical idea of a town’s hinterland by showing how commercial facilities could reshape it.

As the retail market matured, its spatial logic also changed. Initial emphasis on large peripheral sites was followed by the adaptation of central and former industrial locations, and by reinvestment in established centres. Some developments relied on entertainment and catering as well as purchases, while others faced competition from newer premises and changing consumer habits. Kunc and colleagues documented the spread and evolution of Czech shopping centres, including the consequences of the 2008 downturn for expansion plans. Comparative work with Slovak researchers subsequently examined how a centre’s attraction depended on both measurable characteristics and consumer perceptions. Location remained fundamental, but no longer provided a complete explanation. Accessibility, tenant composition, convenience, leisure functions and the qualities attributed to a place helped determine its ability to draw visitors. Retail geography consequently moved beyond plotting outlets towards an analysis of competing urban destinations.

In smaller municipalities, the same commercial changes had different effects. A village shop might remain indispensable for older residents, yet lose trade to a supermarket visited on the way home from a distant workplace. A private car offered access to a wider choice of goods, but the growing expectation of car-based shopping could make local services less viable. This created a cumulative risk where the closure of a shop, post office or bank counter increased the need to travel just as public transport became more difficult to sustain. The resulting

disparities could not be inferred solely from the number of businesses per municipality. Opening hours, prices, the range of goods and the availability of home delivery affected practical access. Research on rural differentiation by Radim Perlín, Silvie Kučerová and Zdeněk Kučera helped put these problems in context. Their typology of Czech rural space demonstrated that development potential varied markedly according to location and socioeconomic conditions, making uniform remedies for service decline unlikely to succeed.

Business services reinforced a different geography. Banking, legal advice, consulting, information technology and other knowledge-intensive activities concentrated where firms could recruit specialised labour and maintain frequent contact with clients and collaborators. Prague possessed the strongest advantages in administrative concentration, international connections and the size of its labour market, with Brno, Ostrava and selected regional centres offering important alternatives. Jakub Ženka and colleagues used the spatial distribution of knowledge-intensive business services to investigate a small post-communist economy and the links between specialised activities and regional conditions. Their work complemented, rather than duplicated, research on industrial production networks. It demonstrated that not all services function as locally consumed amenities: some sell expertise beyond the region in which the work is performed. Their location is influenced by the circulation of knowledge, professional networks and access to skilled workers, even when delivery of the final product can occur at a distance.

The provision of public and socially necessary services followed a different set of objectives. Schools, healthcare facilities, local administration and social care depend in part on the distribution and age structure of residents, but also on institutional decisions about scale and quality. Consolidating a service in a larger centre may improve access to specialist staff or equipment while increasing travel demands for inhabitants of small settlements. Conversely, retaining small facilities can protect local access but require sustained financial support. Transport and service geographies meet directly at this point. A facility’s location is not a sufficient measure of accessibility if a rural resident cannot use it without a car. Studies of micro-regional serviceability and rural development therefore provided a basis for evaluating such decisions through travel opportunities rather than administrative coverage alone. In a settlement system with many small villages, the relationship between service centralisation and territorial fairness remained particularly consequential.

Digital services changed the meaning of distance once again. Online banking, commerce, public information and reservation systems enabled some transactions to be completed without a journey to a physical office or shop. During the COVID-19 pandemic in 2020, restrictions on physical retail accelerated online purchasing, but the trend continued afterwards. The Czech Statistical Office’s 2025 survey found that 68.5 per cent of people aged at least sixteen had purchased goods or services online within the preceding three months, compared with 39 per cent in 2019. Such adoption did not mean that the geography of services had disappeared. Orders required warehouses, couriers, parcel collection points and reliable communications infrastructure. Households differed in digital skills and access, while food, personal care and many public services continued to require physical presence. Digitalisation

altered the balance between travel by consumers and movement of goods, producing new service networks beneath an apparently immaterial interface.

The growth of online platforms also blurred familiar boundaries between retail, transport and tourism. A visitor might select accommodation through a platform, obtain rail tickets on a telephone, use a navigation service to find a restaurant and purchase a locally made product after returning home. Each transaction involved different geographies of ownership, payment, delivery and local benefit. Large platforms could widen a small enterprise's market without guaranteeing that the value generated remained in the municipality. They also concentrated information about customers and demand in organisations that operated across national borders. Economic geographers consequently faced a problem that could not be addressed by counting physical premises alone: how to locate economic activity when sales, management, consumption and fulfilment occur in different places. By 2025 the spatial organisation of services had become a question of both material infrastructure and digital intermediation.

Tourism, meanwhile, occupied an unusually visible position in the country's post-1993 internationalisation. Prague's architectural heritage, historic urban landscape and cultural institutions attracted visitors from a widening range of countries, particularly as European travel became easier. Yet tourism's national geography was never reducible to the capital. The spa towns of western Bohemia, mountain resorts, South Bohemian historic centres, Moravian wine districts and numerous castles, protected areas and cultural landscapes served different markets. Some relied heavily on foreign guests, others on domestic holidays, weekend travel or recurring visitors. The research problem was to distinguish the distribution of tourism resources from the distribution of realised tourism. A beautiful landscape could lack accessible accommodation, while a city with strong transport connections and a dense service economy might accommodate visitors whose activities extended into surrounding regions. Geography thus linked attractions, facilities, mobility and demand.

Jiří Vystoupil and Martin Šauer developed a substantial body of work on this spatial differentiation at Masaryk University in Brno. Their research, together with contributions by Andrea Holešinská, Josef Kunc, Petr Tonev and Daniel Seidenglanz, helped turn tourism geography into a systematic assessment of regional conditions and actual tourist activity. The 2011 monograph Geografie cestovního ruchu České republiky assembled work on the historical development of tourism, natural and cultural prerequisites, accommodation capacity, infrastructure, domestic and foreign visitors and tourism regionalisation. The breadth of the volume was significant. It brought several kinds of data into a common geographical framework instead of measuring destinations through visitor numbers alone. It also identified tourism as a subject requiring both economic analysis and attention to place-specific characteristics. For a country with pronounced differences between metropolitan, spa, mountain and rural destinations, this combination was particularly useful.

Tourism regionalisation became one of the most practical applications of the research. Vystoupil, Holešinská, Kunc and Šauer's 2007 proposal for a new division of Czech tourism regions brought together natural and cultural attractions, facilities, patterns of visitation and organisational questions. The exercise exposed an important distinction between administrative regions and destinations as experienced by travellers. A mountain range, river

valley or historic landscape does not necessarily correspond to a regional government boundary, while a destination promoted as a coherent whole may include settlements whose economic links extend elsewhere. A tourism region drawn only for marketing would have limited analytical value unless its boundaries could be related to resources, accessibility and visitor behaviour. Conversely, a classification based solely on geomorphology might omit the urban services that allow tourism to function. This research established a basis for evaluating territorial tourism policy with methods developed by geographers rather than relying entirely on promotional categories.

Quantitative assessment made such comparisons more transparent. In a 2017 paper, Vystoupil, Šauer and Ondřej Repík presented an analysis of tourism potential intended to support better-targeted infrastructure and development decisions. Their approach recognised that a region's attractions cannot be interpreted separately from the conditions under which visitors can use them. Accommodation supply, transport, complementary activities and the coordination of local actors all influence tourism's economic expression. Potential should not be confused with guaranteed future demand, however. Two municipalities with comparable natural or historical resources may draw very different numbers of guests because one is connected to an established destination network and the other is not. The value of quantitative analysis lies in making those differences visible and testable. It also supports a more careful division of public investment between improving access, conserving resources and building accommodation whose viability remains uncertain.

Rural tourism presented opportunities and constraints quite unlike those of Prague. Farm stays, wine routes, cycling holidays and visits to cultural landscapes could help diversify local economies and support services that relied on a narrow residential market. Kunc, Ondřej Petr, Šauer, Tonev and Vystoupil examined the spatial conditions of rural tourism, paying particular attention to differences among rural landscapes and to wine and farm tourism. Southern Moravia offers a clear illustration of the overlap between agricultural production and a distinctive visitor economy. Viticulture, cellar architecture, regional gastronomy and local events became parts of a shared destination identity, while farms and households could participate to different degrees. This did not mean that every rural municipality possessed an equally marketable form of tourism. The landscape's appeal, entrepreneurial capacity, accommodation and proximity to larger centres mattered, as did the limits of seasonal demand. Diversification was a possibility requiring local conditions, not an automatic cure for agricultural restructuring.

The country's spa towns followed a more specialised trajectory. Karlovy Vary, Mariánské Lázně and Františkovy Lázně retained international reputations grounded in therapeutic resources, architecture and long histories of hospitality. Their tourism depended on a combination of health-related services, accommodation quality and links with foreign markets. The region's economic exposure was therefore different from that of a landscape dominated by short domestic stays. Seasonal patterns, average lengths of stay and dependence on particular visitor groups created distinct risks. The closure of borders or shifts in international demand could affect a spa destination much more sharply than a locality serving nearby residents. Economic geography distinguished these vulnerabilities from the simple volume of guest

arrivals. It asked how specialised local labour markets, property investment and service provision responded when the visitor economy changed. Spa tourism also illustrated that the attractiveness of a place could be both a natural resource and a historically constructed institutional product.

The distribution of tourism in the final years of the period confirms the importance of this variety. The Czech Statistical Office's 2025 statistical yearbook reported approximately 57.2 million overnight stays in collective accommodation establishments in 2024, of which about 18.3 million were in Prague. Such figures demonstrate the capital's dominance but do not describe the full economy of domestic recreation, same-day travel or informal accommodation. They also measure nights spent, not necessarily local expenditure or the distribution of benefits among communities. A district with fewer visitors may still rely heavily on tourism as a source of employment or municipal income. The distinction is evident in spa regions, where the relative weight of tourism in the local economy differs from its national weight. The appropriate territorial indicators therefore depend on the question: tourist arrivals, length of stay, accommodation density, economic value added and local employment reveal different aspects of the same activity.

The pandemic exposed the vulnerabilities hidden by two decades of expanding international travel. In 2020, restrictions on movement and accommodation interrupted established flows of visitors and placed severe pressure on urban hotels and other businesses dependent on international tourism. Domestic destinations experienced different patterns of recovery as restrictions changed and residents looked for holidays closer to home. The episode made the resilience of destinations a more urgent subject than aggregate growth alone. A highly specialised visitor economy could be exposed to the decisions of airlines, international health authorities and markets far beyond the destination itself. At the same time, local responses depended on the structure of accommodation, the presence of domestic visitors, natural attractions and the range of other economic activities. The pandemic did not reverse the longer geography of tourism, but it demonstrated the need to study dependency, adaptability and the capacity of places to manage abrupt disruptions.

Tourism growth also generated new questions about environmental and social limits. Visitor pressure in Prague could produce conflict over housing, noise and the use of historic public space, while in mountain areas it could increase erosion, congestion and demand for parking and waste services. The same tourist expenditure that sustained local businesses might add costs borne by residents or public authorities. Geographical research was well suited to analyse these relationships because the positive and negative effects occurred at different scales. The commercial value of a famous destination could accrue to firms operating across many places, whereas damage to a footpath or the loss of residential amenity was concentrated locally. Destination management consequently required evidence on visitor flows, seasonal peaks, transport routes and carrying capacity rather than a single target for arrivals. By 2025, sustainability had become inseparable from the question of how tourism's benefits were distributed across landscapes and communities.

Taken together, the four sectors reveal a Czech economic geography increasingly concerned with relationships rather than isolated activities. Farm reform changed the management of

land, but its local effects depended on labour markets, policy and commercial links. Transport investment altered travel time, yet its benefits depended on the services, stations and settlements through which people could use it. Retail and other services reorganised everyday movements while digital platforms introduced new distances between consumers, providers and the places where value was retained. Tourism grew by mobilising landscapes, institutions and transport networks, while also making some communities dependent on volatile outside demand. The most durable contribution of Czech research from 1993 to 2025 was not a single map of winners and losers. It was the development of evidence and methods capable of showing why apparently similar places took different paths, and how decisions in one sector repeatedly changed the geographical possibilities of another.

Major Achievements, Research Schools, Leading Scholars and Landmark Publications in Economic Geography

A history of Czech economic geography can be read through a changing set of questions placed before the same map. In the 1990s, geographers asked why some districts gained employment while others lost it, where the new owners of industrial enterprises came from, and whether the apparent stability of the national economy concealed growing differences between places. Two decades later they examined the distribution of research functions inside foreign-owned companies, the institutional conditions of regional innovation, and the capacity of old industrial areas to create new economic activities. By the middle of the 2020s they were also considering how recurrent crises, changes in energy systems and the choices of regional actors could alter an inherited development path. The achievement was not merely an accumulation of regional descriptions. It was the construction of ways to connect economic change with settlement hierarchy, ownership, institutions, public policy and the actual territories in which enterprises operate. This history is especially revealing in a country where industrial traditions were strong, the national territory was relatively compact, and integration into wider European markets occurred with unusual speed. The major Czech contributions emerged from the interaction of long-established geographical approaches with a renewed engagement in international economic geography.

The institutional point of departure was the Department of Social Geography and Regional Development at Charles University in Prague. Its Albertov location has particular significance in the history of Czech geographical scholarship because the research undertaken there linked questions of regional economy with broader studies of settlement systems and social organisation. Martin Hampl, whose work preceded the formation of the independent republic, provided an important part of the conceptual inheritance. Rather than treating a region as an isolated administrative unit, his approach considered how settlements, populations, employment and functions were organised in hierarchies and through relations of dependency. The political changes of 1989 and the creation of the Czech Republic in 1993 supplied a demanding new test of this thinking. Economic decisions were being decentralised and internationalised, but the geographical distribution of cities, transport routes and industrial

capacities could not be remade overnight. For younger researchers, Albertov consequently offered both a body of theory to question and a national landscape whose changes could be traced through successive censuses, enterprise records and regional statistics.

Hampl's 1996 article on the geography of societal transformation expressed the theoretical ambition of the early period. It argued that the recent Czech experience should be interpreted through the relation between social transformation and geographical regularities, especially uneven development. A general improvement in economic performance could coincide with sharper differentiation in the ability of particular places to attract employment or command higher-order functions. This argument differed from an account that simply sorted districts into successful and unsuccessful groups. It asked which geographical relationships were stable, which could be transformed, and how changes in economic activities interacted with the territorial concentration of population. The wider significance lay in giving a small post-socialist country a role in discussions about the general properties of geographical systems. Czech regional disparities were not treated as an exceptional local curiosity to be explained solely by the legacy of state socialism. They became evidence with which to examine hypotheses about hierarchy, concentration and the selective character of economic change.

The 2005 monograph Geografická organizace společnosti v České republice brought this line of work into a substantial synthesis. Its evaluation of transformation during the 1990s drew particular strength from the comparison of economic and population distributions, which did not necessarily move in the same direction or at the same speed. Changes in the spatial distribution of jobs could precede significant residential movement, while an established regional centre might gain functions even when its population growth was limited. The geographical organisation of society thus required more than a single index of regional wealth. Hampl's later studies, including his 2010 account of general types of regional differentiation, continued to connect empirical observations with a theory of differently structured processes. Together with Miroslav Marada, he extended the tradition through research on socio-geographical regionalisation and metropolisation. These works are landmarks partly because they permit researchers to compare moments separated by decades without assuming that the borders of a district capture the economic area within which its inhabitants work and travel.

A second line of achievement began with the measurement of regional inequality under changing economic conditions. Jiří Blažek's 1996 investigation of inter-regional disparities demonstrated why the very low unemployment of the early transformation period could produce a deceptive impression of territorial equality. Differences in wages, entrepreneurial activity and economic performance had to be examined separately, and the choice of statistical measure could affect the apparent magnitude of disparity. His work opened a field of enquiry in which regional development was not reduced to the annual movement of unemployment rates. It brought distributional questions into contact with explanations concerning the location of investment, the positions of urban centres and the varying abilities of regional economies to respond to market competition. The significance of this early article was methodological as well as historical: it showed how to interrogate the measures through which national policy came to recognise a regional problem. Subsequent researchers were

able to begin from a more carefully specified question about inequality rather than assume that any disparity index represented the same economic process.

Blažek also helped to remake the theoretical vocabulary available to Czech geographers. His 1999 article on regional development theories questioned whether the apparently repeated movement between divergent schools represented genuine intellectual progress or a return to familiar positions. Such reflection was timely after several decades in which the domestic discipline had operated with more restricted access to Western theoretical debates. In collaboration with David Uhlíř, he then developed Teorie regionálního rozvoje, first published in 2002 and extensively revised in later editions. The book organised and criticised competing explanations of regional growth and inequality, relating different assumptions about markets, institutions, state intervention and knowledge to their implications for policy. Its value lay not in identifying one universal theory, but in showing why a theory designed for a converging economy might offer poor guidance where investment and skilled labour were becoming more concentrated. The successive editions also document the movement of Czech regional scholarship from post-socialist transition towards evolutionary, institutional and network approaches to development.

Theoretical renewal and empirical research reinforced one another. The initial phase demanded knowledge of structuralist and institutional traditions alongside the earlier quantitative study of settlement hierarchies. With the growing importance of multinational corporations, concepts drawn from global production networks and global value chains entered the analysis of Czech industry. With regional innovation policy, scholars also needed to understand knowledge spillovers, institutional learning and differences between forms of industrial expertise. Blažek's 2012 comparison of regional innovation systems and global production networks was particularly important because it did not presume that the two perspectives were interchangeable. The former asked how the regional institutional environment encouraged learning; the latter investigated the organisation of production and decision-making across territorial boundaries. Bringing them together allowed Czech economic geography to explain why the presence of technologically advanced plants did not necessarily generate an autonomous regional capacity for innovation. It also situated the Albertov tradition within a much wider literature while retaining a specifically geographical interest in the hierarchy of places.

The attention given to research methods was as consequential as the adoption of new concepts. Czech regional data changed in their coverage and territorial classifications as a result of the administrative reforms of the 1990s and the establishment of the fourteen self-governing regions at the beginning of 2001. Researchers compared municipalities, districts, micro-regions, regions and functional urban areas, discovering that conclusions about convergence could depend heavily on the level of aggregation. A regional average could conceal the decline of towns outside a growing metropolitan centre, just as a district's employment figures could miss long-distance commuting. Geographical scholarship responded with more explicit attention to spatial concentration, autocorrelation, local variation and the relation between functional and administrative boundaries. The achievement was not simply the wider use of geographical information systems. It was a stronger

understanding of what a spatial unit represents, what its statistical attributes omit and how changing the scale of observation may alter the substantive interpretation of economic inequality.

Research associated with Pavlína Netrdová and Vojtěch Nosek sharpened these questions. Their work on the spatial concentration and geographical dimensions of socio-economic phenomena showed that statistical variability and the spatial pattern of that variability should be examined together. Blažek and Netrdová's study of the effects of the financial crisis in Central and Eastern Europe similarly demonstrated that different measures of regional unemployment dispersion did not yield an identical account of change. Overall variability could diminish even as the gap between extreme local outcomes widened. Such findings are relevant to policy because resources distributed according to a single national indicator may miss places where disadvantage is locally concentrated. By the 2020s, the Spatial Inequalities Research Centre at Charles University had brought together work on regional economic resilience, unemployment, peripheralisation and quantitative spatial methods. This was an extension rather than a rejection of the Albertov school: the geographical structure of society remained the question, but the methods for observing its internal differences had become more varied and precise.

Another distinctive contribution concerned the geographical consequences of public expenditure. Jiří Blažek and Marie Macešková's 2010 analysis of public capital spending asked whether state investment flowed preferentially towards richer or poorer territories. Infrastructure, public facilities and investment programmes could change a region's long-term prospects, yet their territorial distribution was seldom obvious from ministerial or sectoral accounts alone. By reconstructing spending geographically, the authors made it possible to examine the distributive effects of policies that did not carry the label of regional development. This widened the field beyond questions of private investment and industrial location. A region's prospects were shaped by decisions on transport, education, public services and capital projects, often taken by institutions with objectives different from those of a regional development agency. The broader lesson for economic geography was that the state had not disappeared from the spatial economy after the end of central planning. Its methods of intervention had changed, and their consequences required empirical scrutiny rather than assumptions about either market efficiency or automatic territorial equalisation.

The emergence of the Czech Republic as a major European production location created a further research school around foreign investment and industrial restructuring. Petr Pavlínek's work was influential because it moved beyond the question of how much capital entered a country to examine what that capital actually did in particular places. His 2002 analysis of the passenger-car industry described the selective peripheral integration of Central and Eastern European manufacturing into production systems directed from established centres. Czech factories could be modernised and made export competitive while strategic functions continued to be concentrated elsewhere. The distinction challenged a straightforward equation between foreign ownership and development. It also demanded an investigation of the links between subsidiaries, domestic suppliers, research laboratories and local labour markets. Pavlínek's international academic appointments and sustained research

connections with Charles University made this work an example of scholarship whose institutional geography extended beyond Czech borders. Its Czech subject matter was integral to an international argument about the uneven regional consequences of globalisation.

The 2004 article on the regional implications of foreign direct investment in Central Europe developed the argument by questioning the assumption that large foreign projects necessarily anchored a diversified local economy. A newly constructed plant might introduce technology and employment but purchase inputs largely from an international network, retain only limited research capacity and remain vulnerable to decisions taken by a corporate headquarters abroad. Conversely, a carefully embedded foreign investor might become part of a local network of suppliers, specialised services and technical expertise. This attention to the quality of local linkages established a research programme rather than a single conclusion about investment. It made possible empirical comparisons between plants, industries and towns whose headline production figures looked similar. For Czech economic geography, the result was a more demanding understanding of regional development: the decisive question was not merely where a factory stood, but which activities it controlled, which local relationships it sustained, and where the economic value created through its operations ultimately accrued.

The work of Jan Ženka, developed through collaboration with Pavlínek and subsequently within the University of Ostrava, brought firm-level measurements into this discussion. Their 2011 article on upgrading in the automotive industry evaluated a large sample of companies and differentiated improvements in production processes, products and functions. A subsidiary that manufactured a more complex component had not necessarily acquired responsibility for product design or corporate strategy. The distinction is fundamental because these activities have different employment, skill and income effects. In their 2013 Geografie article, Ženka and Pavlínek related the hierarchy of automotive suppliers to the amount of value captured in host regions, taking account of wages, taxes and retained profits. The research allowed the industrial map to be interpreted through enterprise positions within production networks rather than through sectoral employment alone. It was also a methodological achievement: commercial enterprise information, industrial classifications and micro-regional geographical analysis were brought together to examine differences that general national statistics could not reveal.

The idea of integrated peripheries subsequently gave this work wider conceptual significance. Pavlínek's 2018 study of supplier linkages in the automotive industry examined the conditions under which regions outside the principal corporate centres could become deeply involved in production without controlling the system in which they participated. Its empirical case concerned Slovakia, but its framework illuminated the geographical situation of much of Central European manufacturing, including Czechia. Proximity to established European markets, wage differences, transport connections and preferential access to investment helped explain the attraction of these locations. Their integration remained selective because high-value command functions, intellectual property and decisions on future products did not move automatically with assembly operations. The significance for the discipline was the combination of geographical political economy with detailed observations of enterprise relationships. It encouraged Czech researchers to ask whether the apparent prosperity of an

industrial region was supported by locally rooted capabilities or depended on an advantageous but revisable role in a cross-border division of labour.

Ostrava developed into a particularly important centre for questions arising from this industrial dependence. The Department of Human Geography and Regional Development at the University of Ostrava combined research on old industrial regions with studies of local and regional policy, labour markets, service activities and economic resilience. Its location was analytically useful, not because physical proximity guaranteed superior knowledge, but because the Moravian-Silesian region offered a prolonged sequence of observable changes in mining, metallurgy, engineering and related employment. Researchers including Jan Ženka, Ondřej Slach and Petr Rumpel examined how these inherited specialisations affected the prospects for new economic activities. The city's transformation also made it possible to compare the rhetoric of innovation with the slower reorganisation of industrial land, business practices and workforce qualifications. The Ostrava group participated in international discussions of shrinking cities, regional adaptability and old industrial development paths. Its studies gave the field an essential counterpoint to research undertaken from the perspective of Prague's metropolitan expansion.

Economic resilience became a characteristic concern of the Ostrava research environment. The term was used to distinguish a region's immediate resistance to an economic shock from its subsequent capacity to recover or reorganise. These properties may have different causes: a diversified labour market may suffer less at the outset, while a specialised region may recover rapidly if external demand for its products returns. Research on Czech old industrial regions examined unemployment and economic adjustment after the crisis of 2008–2009 and challenged the idea that a territory's historical industrial structure alone determined its response. By 2024, work by Ženka, Jaroslav Rusnák and Adam Červenka was comparing the effects of several separate recessions in Czech and Slovak regions. The study of the foundational economy—activities supplying essential goods and services—broadened the comparison beyond export manufacturing. Its results suggested that the resilience associated with particular kinds of economic activity was not constant across all crises. This insight made regional policy less susceptible to prescriptions derived from a single historical episode.

The latest phase of this research placed greater emphasis on actors and institutions capable of changing established development paths. Jiří Blažek and Viktor Květoň's 2023 article on agency in old industrial regions brought together approaches that distinguish actions intended to preserve existing activities from those capable of initiating new ones. It also separated the decisions of individual organisations from efforts to alter the regional system itself. A firm might diversify without creating conditions for many others to follow; a regional coalition could attempt to restructure education, infrastructure and research support even before a new industry had emerged. The authors' comparison of contrasting coal-region trajectories illustrated why external investment could not be treated as a sufficient explanation for regional renewal. Their 2025 work on regional governance modes continued this inquiry into the relationship between collective action and industrial evolution. These studies connect Czech evidence to an international shift in regional development theory: places are no longer

understood solely as passive recipients of market forces, but as arenas where actors have uneven capacities to influence economic futures.

A related landmark was the study of regional innovation strategies by Blažek, Pavla Žížalová, Petr Rumpel, Karel Skokan and Petr Chládek, published in European Urban and Regional Studies in 2013. Its comparison of Prague, South Moravia and Moravia-Silesia examined why regional authorities facing broadly similar European policy frameworks developed different capacities for strategic action. The findings drew attention to institutional leadership, coordination and the quality of relationships among public agencies, research organisations and enterprises. The relevance of such work grew after Czech regions acquired self-government and were expected to help formulate development strategies. It shifted evaluation away from an inventory of science parks or grants and towards a history of how regional innovation institutions became capable—or remained incapable—of acting coherently. The research was also useful because its three settings represented distinct economic conditions: a capital-city concentration of research services, a university-based metropolitan economy and a region attempting to renew an older industrial base.

The comparison of biotechnology in Prague with information and communication technologies in Ostrava supplied unusually concrete evidence on knowledge networks. In studies published in 2010 and 2011, Blažek and his collaborators investigated the sources of knowledge used by firms and questioned whether geographical clustering necessarily implied systematic local cooperation. Enterprises situated near universities could depend on partners elsewhere, while firms distant from national research centres might acquire vital expertise through international clients or specialised professional networks. The research showed that the geography of knowledge could not be mapped by counting establishments alone. It required enquiry into actual exchanges, their direction and their organisational form. This conclusion was important for regional development practice because investment in premises or the promotion of a cluster identity would not, by itself, establish the relationships that allow firms to learn. The Prague–Ostrava comparison became a landmark in applying innovation-system concepts to the distinctive institutional and economic inheritance of post-socialist regions.

South Moravia offered another major setting for the encounter between scholarship and innovation policy. Brno’s concentration of universities, engineering traditions, research institutes and modern business services provided conditions for an economy less dependent on the national capital than might have been expected in a highly centralised country. The South Moravian Innovation Centre, established in 2003, became a visible part of the regional support infrastructure, while the launch of the Central European Institute of Technology in 2011 expanded scientific facilities and collaborative opportunities. These developments did not create an innovation system automatically, and geographical research has been valuable precisely because it distinguished institutional provision from effective interaction. The regional experience became an instructive case in the study of leadership, entrepreneurship and the selective diffusion of research capabilities into commercial activity. It also demonstrated that an innovative metropolitan economy could develop outside Prague while still depending on national funding programmes, European resources and links to international scientific and business networks.

The distinction between metropolitan and non-metropolitan development also acquired more sophisticated empirical treatment. In a 2017 study, Ženka, Slach and Andrej Sopkuliak constructed a typology of Czech non-metropolitan regions according to their development mechanisms, firms and structural conditions. Their categories included peripheral territories, single-factory regions, diversified industrial districts and different forms of satellite production platform. The classification mattered because the term ‘non-metropolitan’ had often been used as a residual description for places outside the largest cities. In practice, a small industrial district with internationally connected companies could have a more productive economy than a metropolitan hinterland, while a rural area might combine agricultural activity with manufacturing employment and commuting. The study therefore reduced the risk of treating all territories outside Prague and Brno as variants of one problem. Its result was a contribution to both conceptual clarity and policy design: interventions could be related to the economic mechanisms operating in each type of region instead of applied indiscriminately to every place classified as peripheral.

Work on the location of advanced services supplied another connection between the Ostrava group and wider Czech economic geography. Jan Ženka, Ondřej Slach and colleagues investigated where knowledge-intensive business activities such as information technology and advertising were concentrated, and how their patterns differed among Prague, Brno and Ostrava. Such enterprises can produce for distant customers, yet their location may still depend on specialised labour markets, face-to-face interaction or the industrial clients within reach. Studies of knowledge-intensive services made it possible to test the extent to which a country’s urban hierarchy remained a reliable predictor of new economic activities. They also revealed that an old industrial metropolis could possess a more complicated geography of expertise than suggested by the declining share of traditional manufacturing. This research broadened the economic-geographical understanding of the service economy by connecting its internal spatial patterns to business models, existing specialisations and the morphology of cities. In doing so, it provided a bridge to the study of urban change without losing the central question of how economic value is created and circulated.

The contribution of scholars in Brno cannot be confined to innovation infrastructure. Milan Viturka, working at Masaryk University’s Faculty of Economics and Administration, developed approaches for evaluating regional competitiveness and development potential across Czech micro-regions. His 2010 article on regional disparities linked the quality of the business environment with labour-market conditions and firms’ innovative activity, producing a framework that could be applied systematically to 206 micro-regions and then aggregated for regional comparison. Rather than equating competitiveness with recorded income or a single investment indicator, the approach examined the conditions under which enterprises could operate and adapt. A subsequent model of regional development potential extended the attempt to integrate business environment, innovation and the use of human resources. This was a distinctive contribution from the interface of economic geography, regional economics and applied territorial policy. It widened the institutional base of regional research beyond the university geography departments and encouraged comparison between theoretical measures of development and the practical demands placed on regional administrations.

Research on peripheral regions brought universities in several cities into direct contact. Vít Jančák, Pavel Chromý, Miroslav Marada and Tomáš Havlíček at Charles University investigated how human resources, social capital and local institutions affected development opportunities in territories with limited accessibility or weak employment opportunities. Their analysis of social capital in differently situated Czech peripheries examined participation, trust and the relationships through which a community could respond to local difficulties. In this work, an economic disadvantage could not be interpreted adequately through distance or income alone. The availability of skilled people, a municipality's ability to cooperate and the character of its relationships with outside institutions could matter as much as its transport position. These studies complicated the traditional division between economic and social geography. They also shifted the meaning of development potential away from an inventory of material assets, which was particularly important for small settlements where demographic decline and restricted public services could undermine the value of otherwise favourable physical locations.

A wider inter-university collaboration helped clarify the changing extent of Czech peripheries. Research involving Milan Jeřábek at Masaryk University, Jaroslav Dokoupil at the University of West Bohemia, and David Fiedor and Petr Šimáček at Palacký University Olomouc, together with colleagues from other institutions, resulted in a 2021 study on the new delimitation of peripheral territories. It combined indicators of population, economic activity and transport accessibility at municipal level. The significance of such an exercise was historical as much as cartographic. It allowed the geographers to investigate whether the territorial distribution of disadvantage had remained fixed since the 1990s or had changed with new transport connections, migration and economic restructuring. This work also exposed a basic problem for regional policy: an administrative region can contain both flourishing and vulnerable localities, while an economically weak locality may lie close to a major centre in physical distance but remain poorly connected to its opportunities. A careful geographical definition of peripherality was therefore part of the evidence required for designing territorially appropriate interventions.

Agricultural and land-use research formed another major school with an economic-geographical contribution. Ivan Bičík, Vít Jančák, Leoš Jeleček, Lucie Kupková and their collaborators developed long-term comparisons of land-use change that placed the years after 1993 in a historical sequence extending well before the socialist period. Their research relied on harmonised territorial records, mapped categories of agricultural and non-agricultural land, and an understanding of changing production systems. Bičík and Jančák's 2001 study of Czech agriculture after 1990 examined the sector's restructuring, changing patterns of support and uneven regional consequences. The later synthesis Land Use Changes in the Czech Republic 1845–2010, published in 2015, linked the interpretation of recent change with more than a century and a half of evidence. For economic geography, the decisive point was that the landscape preserved the effects of decisions about ownership, labour and agricultural intensification long after the institutions responsible for those decisions had disappeared. This tradition created an unusually long temporal perspective on regional economic change.

The same school demonstrated the advantages of combining archival geography with modern spatial technologies. Historical land-use categories had to be compared across periods in which administrative divisions, recording standards and local conditions differed substantially. Satellite imagery and digital maps could reveal the contemporary surface, but neither could by itself explain the causes of a change recorded across several generations. Czech researchers brought the sources together and connected land-cover transitions with economic processes such as collectivisation, post-1990 restructuring, marginal-land abandonment and suburban construction. The resulting publications contributed to international land-change science, yet they retained a distinctive geographical attention to Czech farming structures and regional histories. Their importance within economic geography lies partly in refusing to separate productive activity from the spatial consequences it leaves behind. Land was an economic resource, an environmental system and a historical record; different methods were necessary to understand all three functions in relation to one another.

Transport geography supplied another set of achievements through the systematic study of accessibility and functional regions. Miroslav Marada and Viktor Květoň investigated differences in transport opportunities across Czech municipalities and socio-geographical micro-regions. Their 2010 study made clear that a road or rail line on a map was not equivalent to usable access. Frequency, travel time, connections and the location of services could make the practical position of two similarly distant settlements very different. This approach was valuable in a country where dense historical settlement coexisted with rural areas dependent on public transport and with metropolitan regions experiencing rapid commuting growth. Other research on regionalisation and metropolitan cores showed that the location of everyday journeys could reveal changing regional relations more clearly than a static map of administrative centres. The result was a contribution to economic geography as well as transport planning: access to labour, customers, education and public facilities was recognised as a changing component of regional development, rather than a fixed geographical attribute.

Tourism and local service development contributed a different kind of evidence to regional research. The Czech Republic possessed a rich cultural and recreational geography, but the economic role of these resources changed with international mobility, private enterprise, new accommodation markets and the altered demand for domestic travel. Research on tourism demonstrated why numbers of visitors alone were insufficient to describe a region’s gains. The distribution of accommodation, seasonal employment, transport access, local ownership and competing land uses affected how the benefits of visitor spending were retained. Scholars also explored the redevelopment of industrial premises, the emergence of alternative urban attractions and the changing relationship between tourism and everyday life in historic centres. These subjects brought economic geographers into dialogue with cultural geography, planning and environmental research. Their wider methodological significance was to underline that the same landscape may be a workplace, a place of residence, a conservation area and a commodity within a regional visitor economy, with different implications for local development.

The interaction between the university sector and the Czech Academy of Sciences enlarged the field further. The Department of Environmental Geography at the Institute of Geonics preserved elements of a Moravian geographical research tradition after the institutional disruptions accompanying the early 1990s. Its work, and the research published through Moravian Geographical Reports, linked questions of regional development to environmental change, landscape use, industrial legacies and rural transformation. The journal offered an English-language forum for comparative geographical research from its first volume in 1993 and later became co-published with Palacký University Olomouc. Its history is significant because an internationally accessible publication could sustain connections among scholars whose main disciplinary homes varied. Work on regional industries, post-mining landscapes, energy transitions and brownfield regeneration was able to circulate alongside studies of settlement patterns and environmental management. This wider conception of regional development distinguished economic-geographical research from a narrower catalogue of investment incentives or employment trends.

Scientific publishing was itself part of the post-1993 transformation. The long-established journal Geografie, issued under the auspices of the Czech Geographical Society, preserved a forum in which Czech-language empirical studies could appear with internationally accessible titles, abstracts and bibliographic information. It carried many of the landmarks of the period, from early analyses of post-socialist disparities to later investigations of industrial upgrading, metropolisation and regional resilience. Moravian Geographical Reports provided another important outlet, particularly through its continuing English-language publication and the networks of research associated with the Institute of Geonics. At the same time, Czech scholars increasingly published in Regional Studies, European Urban and Regional Studies, Journal of Economic Geography, Economic Geography and European Planning Studies. The change was not simply a pursuit of international visibility. It encouraged questions that could be examined beyond one national case and required greater precision in defining theories, methods and the territorial limits of findings. Czech geographical evidence entered international debates, while those debates supplied new standards against which domestic explanations could be tested.

Several landmarks reveal how the discipline's agenda changed without abandoning earlier insights. Hampl's work supplied a language for hierarchy and differentiation; Blažek and Uhlíř made contemporary regional development theories available for systematic criticism; Pavlínek and Ženka showed that production growth and local value capture need not coincide; and the research on regional innovation strategies explained why institutions with similar formal responsibilities could produce different outcomes. Taken together, these publications offer complementary rather than competing accounts. The settlement system describes relations of centrality and dependence; corporate-network analysis reveals power within transnational production; institutional approaches explain how regions organise collective responses; and the study of spatial inequality shows where the resulting advantages and disadvantages fall. None can provide an exhaustive explanation on its own. Their combination was one of the most significant intellectual achievements of the Czech field, especially as the questions of the

2020s increasingly required information about firms, workers, governments and geographical networks in the same analysis.

The geographical reach of the research schools also became more varied. Albertov remained important for national-scale theory, regional differentiation, innovation systems and production networks. Ostrava's scholars contributed detailed knowledge of industrial change, the spatial distribution of services and the adaptability of non-metropolitan regions. Brno's universities and research institutions developed work on regional competitiveness, borderlands, spatial economic evaluation and innovation policy. Plzeň and Olomouc contributed to studies of peripheral territories, territorial accessibility and regional differentiation. These were not sealed intellectual territories, and many publications resulted from cooperation across universities and with international partners. Some of the most productive research teams were defined by a shared problem rather than a permanent organisational label. The resulting network of institutions helped economic geography avoid the narrowing that could arise if the country were interpreted exclusively through its capital or through one especially prominent industry. Czechia's diverse regions became sites for the comparison of different developmental mechanisms within a common national setting.

The growing ability to work across geographical scales should also be counted among the field's major achievements. Studies of enterprises and international value chains connected decisions made outside Czechia to employment and investment in particular localities. Analyses of metropolitan regions followed commuting and business relationships across municipal boundaries. Micro-regional typologies distinguished industrial platforms from agricultural and service-based districts, while historical land-use datasets connected contemporary economic decisions with much older territorial structures. The availability of population censuses, regional accounts, enterprise-level information, transport measurements and geospatial data allowed these approaches to become increasingly complementary. Each dataset, however, had its own limitations. Company accounts could conceal the location of strategic decisions, regional gross domestic product could be distorted by commuting, and administrative boundaries could fragment functional economies. Czech researchers contributed to international economic geography partly by making these limitations visible and finding analytical methods that could work with, rather than obscure, them.

The influence of geographical research on public decision-making was substantial but should not be exaggerated. Scholars contributed evidence to debates over regional disparities, infrastructure priorities, industrial regeneration, innovation policy and the identification of disadvantaged territories. European Union accession in 2004, the development of regional self-government and successive strategies for regional development enlarged the demand for territorially specific analysis. Nonetheless, published recommendations were not automatically implemented, nor did proximity between universities and regional authorities guarantee the quality of policy. Some research drew attention to the limitations of investment-led development or to the weaknesses of administrative approaches to regional innovation. Such critical findings are part of the contribution, even when they complicate an apparently successful policy narrative. The public value of economic geography lay in providing

independent ways to examine where a programme's benefits appeared, which regions could use them and whether apparent success depended on conditions that a policy could actually influence.

By the end of 2025, the most innovative contributions were increasingly concerned with the capacity to redirect regional development rather than merely observe its outcomes. Research on old industrial territories examined how entrepreneurs, public authorities, educational institutions and intermediaries might act collectively to move beyond an inherited industrial specialisation. Studies of the foundational economy and economic resilience tested the expectation that diversified local activities always protected regions from crisis. Work on regional inequality continued to show that average improvements could coexist with persistent disadvantages at smaller spatial scales. At the same time, the transition towards electric mobility, decarbonisation and more digital production systems presented questions for which the outcomes remained uncertain. The historical record therefore supports a measured assessment of the discipline. Czech economic geography had developed a sophisticated repertoire for analysing transformation, regional networks and institutions, but no single model could guarantee that a region dependent on an established industrial path would successfully create another.

The enduring achievement of Czech economic geography between 1993 and 2025 was its ability to turn a period of profound national change into cumulative scientific knowledge. The field preserved the comparative depth of its settlement and regional traditions while expanding into institutional analysis, geographical political economy, spatial statistics and studies of innovation and resilience. Its leading scholars produced monographs and journal articles that remain valuable because they distinguish economic performance from development capacity, industrial integration from local control, and territorial proximity from effective connection. Research schools in Prague, Ostrava, Brno and elsewhere demonstrated that the most revealing geographical questions often arise where the evidence of one discipline is insufficient: between enterprise strategy and employment, between regional policy and community resources, or between historical land use and contemporary investment. This capacity to cross analytical boundaries gave Czech scholarship a place in international debates without dissolving its attention to particular Czech landscapes and regional histories. The subject at the end of the period was still uneven development, but the means of explaining it had become considerably richer.

Part Ten

Political Geography, Borders and Territorial Identities

Political Geography after 1993: Disciplinary Renewal, Institutional Development and Research Specialisation

The political map of a country can change overnight, whereas the habits by which scholars interpret that map usually change more slowly. On 1 January 1993, the Czech Republic became an independent state with defined borders, institutions and responsibilities in international affairs. Its geographers were consequently faced with new objects of enquiry: a national territory no longer embedded in Czechoslovakia, a democratic electoral system, reconstituted local government and frontiers whose functions were being reconsidered. Yet the intellectual starting point was neither a blank page nor a fully formed political-geographical discipline. Czech geography inherited regional knowledge, cartographic competence and traditions of settlement analysis, while the freedom to examine political power, territorial conflict and competing world views had only recently been recovered. The history of the subject after independence therefore concerns the organisation of inquiry as much as the changing politics of the country itself.

The events of 1989 are essential background, but they should not be confused with the period under examination. The end of one-party rule removed constraints that had narrowed the legitimate subjects and interpretations of geographical scholarship. During the socialist decades, political geography had been particularly vulnerable to ideological prescription because it asked who exercised authority over territory and why that authority was regarded as legitimate. Historical atlases, descriptions of states and studies of administrative divisions could continue, but critical discussion of borders, geopolitical interests or competitive elections was necessarily limited. From the early 1990s researchers could again consider the state as an object of analysis rather than simply a given framework for statistics. The independent Czech Republic provided an exceptionally visible case of a wider intellectual change: the restoration of space as a dimension of political choice, disagreement and institutional construction.

Political geography consequently took shape at the meeting point of several disciplinary traditions. From geography it drew attention to scale, location, accessibility, settlement networks and the uneven distribution of populations and resources. From political science it adopted questions about representation, party competition, institutional design and the exercise of state power. International relations supplied debates about sovereignty, regional organisations and security; history contributed the evidence required to interpret territorial claims and changing collective identities. This mixture was productive but rarely seamless. The same border might appear as a measurable obstacle to cross-border commuting in one study, a legal jurisdiction in another and a symbol of national identity in a third. The pluralism that

characterised Czech political geography was thus a genuine analytical opportunity, even though it complicated attempts to establish a single institutional home or a common theory.

The first years of independence made the spatial dimensions of constitutional arrangements unusually tangible. The dissolution of Czechoslovakia transformed a former internal administrative boundary into an international frontier, while the Czech lands retained their historically varied landscapes of local government and regional attachment. Arguments about decentralisation took place against a legacy of many small municipalities and the strong administrative position of Prague. A political-geographical approach examined not only the number and boundaries of governmental units but also whether their territories corresponded to patterns of daily interaction and residents' sense of belonging. A district could be convenient for state administration without describing the social reach of a regional centre. Likewise, a historic land could survive strongly in collective memory without possessing contemporary governing institutions. Such contrasts became basic material for the renewed discipline.

The restoration of competitive elections brought a different source of geographical evidence. Electoral results were reported at fine territorial scales, offering repeated observations of the relationship between social structure and political choice. The pioneering geographical study of the 1990 parliamentary elections by Jiří Blažek and Tomáš Kostelecký had appeared before independence, and it immediately demonstrated the potential of multivariate analysis in a field long deprived of genuine electoral variation. After 1993 the growing sequence of elections made it possible to distinguish transient enthusiasm for a party from an enduring regional pattern of support. Researchers could ask whether industrial districts, borderland municipalities, metropolitan suburbs or rural peripheries displayed distinct political alignments. These questions were not confined to mapping winners. They required an understanding of party systems, the organisation of electoral constituencies and the risk of mistaking an aggregate geographical correlation for the behaviour of individual voters.

A lasting feature of this early revival was the need to build Czech-language teaching materials. Students entering geography programmes in the mid-1990s could no longer rely on accounts of world politics framed primarily by ideological blocs or simplified lists of strategic states. In 1996 Vladimír Baar, Petr Rumpel and Petr Šindler published Politická geografie at the University of Ostrava. Its importance lay in its timing as well as in the material it presented. A dedicated university text demonstrated that political geography could again be taught as a field with its own concepts and questions. It also signalled the relevance of Ostrava, a city near several historical and state boundaries, as a place from which to examine territorial change. The re-establishment of specialist teaching preceded the full consolidation of doctoral training and a stable body of internationally visible research.

A more extensive intellectual synthesis followed in 2000 with Stát, prostor, politika: Vybrané otázky politické geografie, edited by Petr Jehlička, Jiří Tomeš and Petr Daněk. The volume brought together contributors whose topics ranged from geopolitical thought and war to electoral systems, development, globalisation and international environmental politics. The arrangement demonstrated the breadth of the emerging field. Political geography was not restricted to drawing boundary lines or naming capitals; it addressed the processes through which unequal development, state institutions and conflicts acquired territorial form.

Particularly important was the willingness to place domestic transformation beside problems arising outside Europe. This offered Czech students a way to consider their country's recent experience without treating it as the universal model of political change. A renewed syllabus became, in effect, a statement about what kinds of questions Czech geographers could now legitimately ask.

The collaborative research project Political Geography of the World, supported by the Czech Science Foundation in 1998–1999, supplied an institutional bridge between teaching and research. Based at Masaryk University with participation from Charles University, it sought to introduce theoretical and methodological developments that had received limited attention in Czech geography. Its intended outputs included analyses, maps, articles and a scholarly teaching text. The project illustrates an early stage in disciplinary reconstruction when producing a shared conceptual vocabulary was itself a research task. Its significance cannot be measured solely by the number of publications attributed to it. More consequential was the attempt to connect researchers across universities, to reassess inherited explanations of political space and to create materials from which students and younger colleagues could pursue more specialised enquiries.

Three broad research orientations became visible, although their boundaries were permeable. A spatial-analytical orientation sought regularities in the distributions of votes, institutions, conflicts or administrative resources. A political-economic orientation asked how unequal power and development were reproduced across countries and regions. An interpretative orientation examined the language, memories and representations through which places became politically meaningful. None was uniquely Czech, and individual scholars could employ more than one. Their coexistence nevertheless helped the discipline escape the older assumption that political geography was a catalogue of territories. The researcher was increasingly required to specify whether a map was an outcome to be explained, a representation needing criticism or an instrument through which decisions were made. That distinction became more pressing as digital geographical information became widely available.

Territorial administration formed a natural early specialisation because the new republic had to reconsider the distribution of authority within its borders. The establishment of self-governing regions at the turn of the millennium gave researchers an opportunity to investigate the relationship between legal reform and functional geography. The fourteen higher-level territorial units, including Prague, were not simple reproductions of the historic lands or of contemporary metropolitan labour markets. They combined political compromise with administrative reasoning. Scholars could examine how decision-making powers, tax revenues and public services were allocated among levels of government, and whether these arrangements increased responsiveness outside the capital. This was a political-geographical problem because the effectiveness of decentralisation depended partly on the size, configuration and social coherence of the territories to which authority was assigned.

Petr Daněk's work on local political culture in the Czech borderlands showed the value of studying institutions through the histories of particular places. Municipal government in districts affected by wartime population transfers and subsequent settlement could not

always be understood from national legislation alone. Local association, historical continuity and residents' attachments influenced the capacities through which democratic institutions were rebuilt. His geographical investigations of the borderland's conditions for democratic local administration also made a broader methodological point. Institutions operate within social landscapes shaped by previous regimes, changing populations and physical distance. Research needed to compare municipalities carefully rather than assume that the same constitutional reform would have identical local consequences. In this sense the borderlands offered a test of how historical rupture continued to affect contemporary political life.

The geographical study of borders changed with the gradual opening of Central Europe. In the early 1990s, the Czech Republic's frontiers were still sites of differentiated legal, economic and administrative systems. Cooperation along the German, Austrian, Polish and Slovak borders expanded, particularly through European programmes and municipal partnerships. The accession to the European Union in 2004 and entry into the Schengen Area in 2007 altered practices of movement and border control, but neither event abolished the political significance of national territory. A border could become less visible to a commuter while remaining relevant to language, schooling, taxation, public-service provision or political memory. Czech researchers therefore came to treat bordering as an ongoing set of social and institutional practices rather than as a fixed line whose importance could be read directly from its legal status.

Ostrava developed one of the clearest institutional concentrations of political-geographical expertise. The University of Ostrava's Department of Human Geography and Regional Development combined political and cultural geography with economic and regional perspectives. Its programmes connected the study of statehood, ethnicity and conflict to the geographical analysis of particular world regions. Doctoral accreditation in political and cultural geography followed in 2007, and accreditation for habilitation and professorial procedures was obtained in 2014. These steps were substantial because they helped create a local mechanism for training new scholars and recognising advanced academic work. Later adjustments to programmes culminated in the combination of political and economic geography within a doctoral framework in 2021. Institutional development was therefore cumulative rather than a single act of foundation.

The Ostrava tradition was also shaped by scholars whose interests crossed political and cultural themes. Vladimír Baar brought geographical perspectives to the study of peoples, nationalism, state structures and post-Soviet territories. Tadeusz Siwek's research on the perception of regions and ethnic identities added an important corrective to the idea that an administrative map exhausts the meaning of territory. The younger scholarly environment included Tomáš Hoch, Vincenc Kopeček and Barbara Baarová, whose work developed themes of de facto states, minority politics and geopolitical conflicts. These specialisms made a regional university a contributor to international debates. They also encouraged researchers to test concepts such as recognition, sovereignty and national self-determination against cases where legal status and effective territorial control did not coincide. A robust geographical account had to attend to institutions, people and spatial practice together.

The contribution of scholars with substantial international academic experience was especially important to this environment. Petr Dostál, whose career had included decades at the University of Amsterdam, connected work on democratic transformation, territorial administration and European integration with comparative social-scientific methods. His 1998 study of political and economic change across post-communist countries illustrates the use of systematic cross-national explanation; his later investigation of public attitudes towards EU enlargement brought these questions closer to Czech accession. Bořek Hnízdo, teaching political science and political geography at Charles University, helped reopen discussion of geopolitical concepts during the 1990s. Their different trajectories showed that disciplinary renewal involved both the movement of people and the reassessment of ideas.

Charles University provided another, differently organised centre of political-geographical inquiry. Within its Faculty of Science, research and doctoral training in regional and political geography formed part of a broader social-geographical tradition attentive to settlement systems, regional differentiation and the interaction of society with territory. Political questions could accordingly be investigated through the changing geography of institutions, elections, identity and environmental governance. The university's Faculty of Social Sciences offered an additional setting in which political geography and geopolitics were examined through political science, area studies and international relations. This plurality created opportunities for exchange but also required clarity about disciplinary premises. A study of the same conflict might use geographically situated historical interpretation, comparative institutional analysis or a model of strategic behaviour. The proximity of these approaches did not make their underlying assumptions identical.

Masaryk University in Brno occupied a significant position at the intersection of geography and electoral research. Its scientific and social-science faculties provided different routes into the subject, particularly through the analytical treatment of voting behaviour and comparative politics. Researchers associated with the Brno environment examined how social composition, regional histories and political competition contributed to the territorial distribution of party support. The development of a public educational resource on political geography reflected this combination of conceptual and empirical interests. Its presentation of spatial-analytical, political-economic and interpretative perspectives introduced students to the coexistence of methods within the field. Brno's importance lay partly in this movement across departmental boundaries, showing that disciplinary renewal could occur through collaboration rather than the creation of a single, exclusive academic unit.

The Academy of Sciences added another kind of institutional contribution. At its Institute of Sociology, electoral behaviour and local government were studied with an intensity that made geographical evidence central to questions usually classified as sociology or political science. Tomáš Kostelecký and his collaborators used electoral returns and municipal characteristics to trace regional patterns across successive democratic elections. This research made long-run comparison possible and drew attention to the scale of analysis. The smallest municipalities revealed local variation that disappeared in district-level summaries, while broad regional groupings were sometimes necessary to identify durable historical contrasts. The resulting publications demonstrate that political geography's empirical development did

not belong to university geography departments alone. A substantial part of its evidence and method was produced in institutions with different disciplinary names.

Electoral geography became one of the most measurable specialisms because its basic observations were regularly collected and geographically identified. Yet a technically precise distribution of votes was not self-explanatory. A region could favour one party because of industrial employment, a history of religious affiliation, the presence of a strong local candidate or a combination of factors operating at different scales. Scholars therefore examined both the spatial persistence of electoral patterns and their changing social foundations. Methods such as regression, cluster analysis, measures of variation and mapping made comparisons systematic. They also introduced familiar statistical dangers: spatial autocorrelation, boundary changes and ecological inference could produce persuasive-looking conclusions unsupported by individual evidence. Methodological maturity involved learning to articulate these limitations instead of presenting electoral maps as direct portraits of public opinion.

The comparative dimension strengthened after researchers had accumulated several elections under the new party system. Petr Voda's 2015 monograph compared Czech and Austrian electoral geography from 1990 to 2013, asking whether the post-communist experience continued to influence the territorial organisation of political preferences. The comparison drew upon differences in party systems, social divisions and the temporal stability of electoral support. Its importance for Czech scholarship lay not simply in judging one country against another but in making the conditions of comparison explicit. A stable geographical pattern could reflect long-lived party organisations as well as the social attributes of voters. Differences in political history mattered because they shaped which choices were available to electorates in the first place. Political geography thus moved beyond a narrowly national chronology while retaining attention to specific institutions.

Metropolitan growth added a new geographical dimension to political behaviour. Suburban migration changed the social composition of municipalities surrounding Prague and other major cities, often faster than local institutions could adjust to new demands. Research on metropolitan political behaviour connected residential change with turnout, political competition and local decision-making. It was possible to compare municipalities with substantial new housing, older suburban settlements and rural localities undergoing more modest demographic change. Yet the relationship between suburbanisation and voting could not simply be imported from Western European models. The Czech housing transition, the location of employment and patterns of municipal fragmentation were distinctive. This line of work demonstrated how a political question about representation could be enriched by the evidence and methods of urban and population geography without losing its own analytical focus.

One conceptual advance was the gradual replacement of a purely state-centred account of territory with the idea of multi-scalar governance. Power could be exercised through a municipality, a region, a national ministry, a European body or an informal cross-border network. Each setting had different resources and methods of accountability. A decision about transport, environmental protection or development subsidies might originate outside the territory where its effects were most visible. Researchers were consequently obliged to track

relationships between institutions rather than assume that authority flowed neatly downward through a fixed hierarchy. This perspective also exposed a difficulty of decentralisation: local discretion could grow at the same time as local authorities became dependent upon external funding rules or transnational regulatory standards. The politics of place was increasingly a politics of connections among places.

European integration gave this argument an unusually concrete setting. Negotiations before accession, implementation of European law and involvement in cross-border programmes brought new actors into Czech territorial governance. The EU was not a single geographical scale replacing the nation-state; it was a network of policy instruments, legal obligations and arenas for political negotiation. Researchers examined how national institutions translated common rules into local practice, and why outcomes varied among regions despite similar formal requirements. They also considered the changing symbolic position of Central Europe in public discussions of identity and development. The geographical problem was to show where authority resided, through which routes resources and decisions travelled, and how localities experienced policies designed at a distance. These questions connected political geography to regional studies without making either field subordinate to the other.

Environmental politics became an important specialised route into the study of state power. Czech environmental movements had played visible roles in the transition from state socialism, and the subsequent transformation of environmental governance supplied material for research on institutions, knowledge and policy. Petr Jehlička's investigations considered the history of environmental activism and the influence of European integration upon the ways environmental issues were framed. His collaborations also challenged simplistic accounts in which domestic organisations merely copied Western ideas after 1989. Czech activists possessed earlier experience, priorities and intellectual networks that shaped their later engagements. Such findings carried a wider political-geographical implication: political practices cannot be adequately understood by identifying the territory from which a policy model supposedly originated. The channels through which ideas travel, and the manner in which they are adapted locally, must also be studied.

The opening of academic debate also allowed renewed scrutiny of geopolitical language. Classical geopolitics had been associated with claims about strategic necessity and the supposed natural interests of states; contemporary scholars were increasingly cautious about those assumptions. The value of geopolitical analysis depended on distinguishing material constraints from political interpretations of them. Mountains and transport corridors could influence military or commercial choices, but they did not dictate a government's intentions. Historical experiences of imperial domination made this issue particularly salient in Central Europe. Research could investigate how political actors invoked Europe's centre, eastern peripheries or traditional spheres of influence as persuasive descriptions of the world. A geopolitical map was then understood as a politically consequential representation, not merely an objective diagram of physical distances.

This concern encouraged a dialogue between conventional and critical approaches. Analysts concerned with security and interstate conflict could employ comparative cases, demographic data or formal reasoning to explain strategic outcomes. Critical scholars might instead

examine the narratives through which politicians, journalists and experts represented external dangers and legitimate interests. The two approaches asked different questions, but each could correct limitations of the other. Material capacities matter even when they are described through selective language; representations matter even where territorial constraints are real. Czech political geography's small academic community made this dialogue potentially manageable, while differences in disciplinary training sometimes made it contentious. The result was not a comprehensive theoretical synthesis but an increasing awareness that explanations must be judged in relation to the questions and evidence they use.

A particularly revealing discussion of these differences appeared in Jan Kofroň's 2017 article Shattered Spaces of Political Geography. Writing from the interface between political science and geography, he examined divisions concerning epistemology, explanatory ambitions, methodological preferences and attitudes towards generalisation. His analysis disputed the assumption that sharing an interest in territory automatically produces interdisciplinary cooperation. Geographers and political scientists could pursue similar puzzles while working with incompatible standards of evidence or distinct expectations about what a satisfactory explanation should contain. The article suggested that attention to counterfactual reasoning and an openness to detailed case knowledge might improve mutual understanding. It remains valuable as a diagnosis of the conditions under which a relatively small national field could become intellectually fragmented despite its thematic breadth.

Regional specialisation outside Czechia represented another important direction of growth. Researchers who had begun by examining the post-socialist transformation of Central Europe turned to the successor states of the Soviet Union and to political systems where sovereignty remained contested. The Caucasus offered especially demanding cases because internationally recognised borders, effective control and competing historical narratives could diverge sharply. The choice of such areas was not merely an expansion of geographical coverage. It required new linguistic skills, regional field knowledge and conceptual care concerning recognition, patronage, political mobilisation and violence. Scholars working in this tradition confronted the danger of treating categories such as nation, ethnic community or separatist movement as stable objects independent of historical context. Their studies situated territorial conflicts within institutions and social relationships that changed over time.

The work of Tomáš Hoch, Vincenc Kopeček and colleagues at Ostrava illustrates how research specialisms matured around these problems. Studies of Abkhazia, South Ossetia and other post-Soviet territories examined strategies of political legitimation and the relationship between local authorities and external patrons. The edited volume De Facto States in Eurasia, published in 2020, placed several cases within a comparative framework. This scholarship supplied evidence for an important distinction: international recognition is not identical to the existence of administration, political institutions or social attachment to a territory. At the same time, the presence of local institutions does not dissolve questions about coercion or the rights of displaced populations. Political-geographical research became more precise when it preserved these distinctions and avoided reducing contested statehood to a single moral or legal label.

Ethnicity and nationalism were explored through a similarly differentiated vocabulary. The political relevance of language, religion and historical memory varied among places, and territorial identities could be overlapping rather than exclusive. Work on regions such as Cieszyn Silesia demonstrated that a borderland might be described differently by neighbouring communities without either description being simply fictional. Studies of post-Soviet minorities and national movements likewise distinguished official categories from the ways people understood their everyday affiliation. The central question was not only where a population lived but how a particular definition of community became politically authoritative. Such analysis brought field interviews and archival interpretation into closer contact with geographical mapping. It also encouraged ethical care when researchers represented groups whose political circumstances were contested or precarious.

Political geography extended beyond statehood and formal institutions into the investigation of political practices in ordinary places. Municipal boundaries shaped access to schools, transport and public services, while decisions about construction or environmental protection could generate conflict over the use of a familiar landscape. Researchers attentive to local governance examined participation, trust and the unequal capacities of communities to influence decisions. A village with few residents might possess formal autonomy yet lack specialist staff or bargaining power; a metropolitan district might have substantial administrative resources but face weak attachments among rapidly changing populations. Such cases highlighted the difference between a right written into law and the practical capacity to use it. The significance of territory lay partly in the institutions available to those who inhabited it.

Another methodological development concerned the use of geographical information systems and increasingly detailed electoral data. Digital processing permitted researchers to relate local returns to census variables, commuting patterns or historically changing municipal boundaries. Spatial statistics could distinguish clustered concentrations from variation that appeared only because of administrative aggregation. Yet technical advances also introduced demands for transparency. Maps are choices about classification, colour, scale and territorial units; a correlation can change when the units of analysis are altered. Political geographers became more attentive to sensitivity testing, the documentation of datasets and the interpretative limits of statistical models. These practices did not replace historical explanation. Rather, they allowed empirical findings to be examined critically and reproduced under clearly specified assumptions.

Qualitative methods developed in parallel. Interviews, documentary analysis, participant observation and the interpretation of public narratives were suitable for questions that electoral returns or official boundaries could not answer. Researchers could ask how residents understood a border, how a minority organisation maintained support or how conflicting stories of sovereignty circulated through institutions and the media. Fieldwork was particularly important in regions where publicly available statistics were incomplete or politically contested. It also demanded care about selection, translation and the position of the researcher. An interview conducted under conditions of insecurity cannot be treated as a transparent measure of collective opinion. The methodological contribution of qualitative

political geography therefore included both access to otherwise invisible processes and explicit reflection on the conditions under which evidence was obtained.

The internationalisation of publication and training altered the intellectual environment of the discipline. Czech researchers gained broader access to English-language scholarship and joined conferences and networks in which concepts developed in different national settings could be compared. Publication in international journals helped place Czech cases within debates about post-socialist governance, territorial identities and electoral behaviour. Nevertheless, international visibility brought a tension between general concepts and locally significant questions. A study written for a global audience sometimes needed to explain legal or historical arrangements familiar to Czech readers, while domestic publications could develop issues of direct public concern without receiving comparable international attention. A mature research system required both forms of communication and careful translation between them.

The political geography of development provided a further connection to global scholarship. Petr Daněk's work on colonialism, unequal development and the discourse of development, published within the 2000 collective volume, broadened the field beyond the immediate geography of a transforming Czech state. By tracing how colonial relations and subsequent institutions shaped the unequal distribution of resources, this research introduced questions about power at the global scale. International assistance could be studied not merely as a transfer from affluent to poorer states but as a relationship organised through political priorities and representations of need. These ideas later resonated with analyses of globalisation, environmental governance and the circulation of knowledge. Political geography in the Czech setting could thus connect regional specialisation with broader theoretical questions about the making of spatial inequality.

The geography of knowledge production itself became an object of critical interest. Research agendas are influenced by grant programmes, publication requirements, language hierarchies and access to international networks. Scholars working in relatively small academic systems may face strong incentives to adopt the questions and terminology favoured by larger centres of research. Yet their close knowledge of Central and Eastern Europe can reveal assumptions that go unnoticed elsewhere. In the Czech case this tension was particularly clear when debates about environmental governance or post-socialist institutions were presented as one-way transfers of Western knowledge. Reflection upon the conditions of scholarship therefore belonged within political geography, because the authority to define a problem and the uneven distribution of academic resources also possess spatial dimensions.

The expansion of European and global research networks changed doctoral education. Students could draw upon foreign supervisors, undertake fieldwork abroad and compare cases rather than confine dissertations to national administrative statistics. At the same time, the work of maintaining specialised programmes depended upon staffing, research funding and the ability to support small cohorts. Ostrava's doctoral accreditation in 2007, its subsequent qualification procedures and the 2021 reorganisation of doctoral programmes show institutional adaptation across two decades. Charles University's regional and political geography training reflected a different combination of multiscalar governance, state studies

and environmental issues. Such programmes indicated that political geography had moved beyond occasional lectures or personal research interests towards recognised pathways of advanced training, even though the field remained modest in size.

The resulting academic landscape was deliberately plural rather than centrally coordinated. Prague combined a strong geographical tradition with political science and Academy-based electoral studies; Brno fostered connections between political analysis and geographical methods; Ostrava established a particularly identifiable cluster in political and cultural geography. Researchers at other institutions contributed through border studies, historical geography, political sociology and regional development. No single centre monopolised the subject's vocabulary or agenda. This arrangement made national research more diverse but sometimes dispersed results across different journals and disciplinary classifications. It also means that a history based only on institutions bearing the formal label of political geography would overlook some of the field's most consequential publications. The boundaries of a discipline are partly intellectual and cannot be inferred simply from departmental names.

Scientific journals played an important role in making the field visible. Geografie and AUC Geographica published research whose analytical focus ranged from regional voting and spatial inequality to borders and historical territorial identities. Political-science journals such as Acta Politologica provided additional venues for debates about theory, evidence and geopolitical interpretation. International outlets widened the audience for case-based research on the Caucasus and related regions. These publication channels differed in disciplinary expectations, languages and readerships. Their coexistence showed the benefits of interdisciplinarity but also made cumulative discussion harder when scholars working on comparable problems did not read the same literature. Attempts to bridge these forums were therefore a substantive part of disciplinary development, not merely a matter of professional networking.

By the 2010s and early 2020s, electoral research was increasingly attentive to the geographical distribution of distrust, resentment and populist support. Rather than infer a uniform explanation from national election totals, scholars examined how local economic conditions, peripheral status and the history of political competition related to changing electoral coalitions. Jonáš Suchánek and Jiří Hasman's 2023 analysis of radical-right voting between 1992 and 2021 demonstrated the value of a long temporal perspective in distinguishing different political movements rather than treating them as a single continuing force. The study also showed why geographical concentrations of support cannot automatically be reduced to a single social grievance. Similar election outcomes may arise through different combinations of demographic structure, local experience and political mobilisation. Spatial comparison is strongest when it tests explanations instead of merely naming disadvantaged regions.

A systematic review by Dominik Kevický, published in 2021, offered another form of self-assessment. Examining studies of Czech and Slovak parliamentary elections, it found that the search for factors behind the spatial differentiation of voting dominated the literature. Turnout and the geographical dimensions of representation received less attention, while the use of explicit theory and qualitative methods was uneven. These findings are important precisely because they complicate a simple narrative of uninterrupted methodological progress. The

availability of detailed data had encouraged quantitative analysis, but some politically significant questions remained comparatively neglected. A discipline's renewal is not complete merely because it produces more publications. Its achievements must also be judged by which questions become researchable, which remain marginal and how clearly researchers explain their analytical choices.

Contemporary political geography also faced the challenge of rapid geopolitical change. Developments in Russia's relations with its neighbours, conflict in the Caucasus and the full-scale invasion of Ukraine in 2022 renewed public attention to borders, security, displacement and state sovereignty. Czech scholars brought regional expertise and methodological tools to debates whose political urgency was unmistakable. Scholarly analysis nevertheless required maintaining a distinction between the events themselves and the evidence available to explain them. Assertions about historical rights, ethnic territories or strategic imperatives needed examination rather than repetition. The task of academic political geography was not to replace political judgement with a supposedly neutral map, but to clarify the spatial assumptions, institutional relationships and consequences at issue. The discipline's credibility depended upon resisting both geographical determinism and the reduction of complex places to slogans.

Several intellectual continuities can nevertheless be identified across the entire period. Attention to the territorial organisation of society remained important even as the research agenda expanded from domestic administration to distant conflicts. The combination of historical awareness and detailed regional knowledge continued to distinguish many Czech contributions. A growing reliance on systematic comparison encouraged the field to move from recording spatial differences towards explaining them. At the same time, research on identity and discourse challenged the assumption that all political-geographical phenomena could be expressed adequately through numerical indicators. The tension between these approaches was not simply an obstacle to be overcome. It helped researchers recognise that a convincing explanation of political space must match its evidence to the kind of power, practice or representation being studied.

The principal limitation was fragmentation. A small scholarly community spread across geography, political science, sociology and area studies could produce insightful work without creating sustained conversation between its branches. Research evaluation systems often rewarded international specialisation, while applied concerns about local governance and cross-border cooperation demanded accessible Czech-language communication. Training in quantitative inference was uneven, just as interpretative fieldwork and historical comparison were not equally prominent in every research centre. These asymmetries mattered for the questions scholars were able to formulate. They also suggested priorities for future work: better exchange of data and concepts, careful comparison of research designs, and a willingness to treat evidence from different traditions as potentially complementary rather than mutually exclusive.

By the end of 2025, the renewal of political geography in the Czech Republic could be recognised in the existence of specialist textbooks, research programmes, accredited training, international publications and identifiable areas of expertise. The field had moved from the reintroduction of politically sensitive questions towards more differentiated enquiry into

governance, elections, borders, nationalism, environmental politics and contested sovereignty. Its institutional centres were neither identical in purpose nor isolated from neighbouring disciplines. The significance of this history lies in the gradual creation of a scholarly capacity to examine how political authority becomes organised, experienced and challenged in space. The following sections can therefore consider borders, electoral behaviour and geopolitical conflict in greater depth against a background in which those subjects are understood as related, but methodologically distinct, achievements of Czech geographical research.

State Borders, Borderlands and Cross-Border Cooperation in the European Context

The border that a traveller crosses in a few seconds can shape a village for generations. This apparent contradiction became one of the central questions of Czech political geography after the establishment of the independent Czech Republic on 1 January 1993. Over the following three decades, the country's frontiers were simultaneously lines of state jurisdiction, reminders of interrupted histories and settings for new forms of regional cooperation. The integration of Czechia into European institutions reduced many of the practical costs of crossing them, yet it did not erase the differences between neighbouring labour markets, planning systems or communities. Researchers consequently had to move beyond a simple distinction between closed and open borders. They sought to understand how geographical position, historical experience and public policy affected the ways borderlands developed. Their work traced a change in the meaning of the frontier itself: from a presumed edge of national territory to a place where political decisions could be observed in everyday economic, social and cultural relations.

Independent statehood made the Czech–Slovak frontier a particularly revealing starting point. Before 1993, it had been an internal division within a federation, although administrative systems and local identities already gave it practical and symbolic significance. Independence turned this line into an international boundary between two successor states. Decisions about customs, travel documents, trade and public services acquired a new territorial dimension, even though linguistic proximity and family connections continued to link communities on either side. The geography of the new border differed from that of the western and northern frontiers. It lacked the same long-standing association with the Iron Curtain, while the Moravian–Slovak highlands and the Carpathian landscape imposed their own limits on communication. For researchers, the division offered an opportunity to distinguish the effects of a new political boundary from the effects of terrain and inherited settlement networks. A line newly recognised in international law did not instantly create a new social region.

Czechia's external position gives this subject particular geographical depth. Germany lies to the west and north-west, Poland to the north and north-east, Slovakia to the east and Austria to the south. The Šumava and Bavarian Forest, the Ore Mountains, the Krkonoše, the Jeseníky

and the Carpathian ranges shape considerable portions of the frontier. Rivers and mountain passes channel movement into corridors, while the pattern of towns often reflects older routes and economic relationships. Border areas therefore do not form a uniform ring around the country. A municipality beside a busy crossing near a regional capital has different prospects from one at the end of a mountain valley, even when both lie equally close to an international boundary. The political significance of these physical conditions changed as roads were rebuilt, new crossings opened and national parks acquired international partners. Czech geographical research increasingly treated the border as one element within a wider network of accessibility rather than an adequate explanation in itself.

The territorial inheritance of the twentieth century nevertheless remained indispensable. Before the Second World War, substantial parts of the present Czech borderlands had predominantly German-speaking populations, while the Těšín/Cieszyn region and other areas contained overlapping Czech, Polish and regional affiliations. War, occupation, the forced displacement of German-speaking inhabitants after 1945 and subsequent resettlement transformed the social geography of numerous districts. In parts of the western and southern frontier, Cold War restrictions further interrupted settlement and communication. The surviving pattern of villages, abandoned buildings, land uses and transport routes therefore represented several distinct historical interventions, not merely an enduring geographical disadvantage. Post-1993 researchers brought historical maps, demographic records and local testimony into dialogue with contemporary statistics. They found that the apparent marginality of a borderland could be reproduced by weak institutional continuity or fragmented settlement even after the border itself became easier to cross. Historical geography thus supplied political geography with an explanation for why equally permeable frontiers did not generate equally integrated regions.

The change beginning in 1989 was especially visible along the Austrian and German borders, where political controls had separated neighbouring settlements from their former hinterlands. Reopening crossing points and restoring contacts created immediate possibilities for visitors, entrepreneurs, local councils and families. Nevertheless, physical permeability was not synonymous with economic equivalence. Differences in wages, purchasing power, property markets and municipal resources shaped the direction of early cross-border exchanges. Some Czech communities gained customers or employment opportunities; others experienced traffic, land speculation or competition for local businesses. The arrival of travellers could make a border town more active without necessarily strengthening its long-term productive base. For geographers, these contrasting outcomes undermined the assumption that removing a barrier automatically produced development. They began to compare the capacity of local organisations, the availability of infrastructure and the degree to which relationships could survive beyond the first years of political enthusiasm.

Early research also confronted a problem of definition. A state border is a juridical line, whereas a borderland is a geographical area whose extent must be argued rather than simply drawn. A narrow strip measured by distance from the frontier may include inaccessible mountains but exclude a town whose economy depends heavily on a neighbouring country. A district-based definition allows comparison with official statistics, yet administrative boundaries can conceal

strong differences within a single district. Functional definitions, based on commuting, trade or service use, may change rapidly when a major crossing is opened or restrictions are imposed. Researchers therefore examined several kinds of border effect: separation, filtering, contact, exchange and the selective concentration of particular activities. These effects could operate at different scales and at different moments in the same locality. The distinction mattered because empirical findings were sensitive to the chosen territorial unit. A decline measured for an administrative district did not necessarily describe every village within it.

The Czech discussion of border effects drew on international theories of regional development, but its evidence could not be fitted neatly into a single imported model. Classical centre–periphery approaches highlighted remoteness and dependence on distant decision-making centres. More recent institutional and relational approaches asked whether municipalities could establish partnerships across jurisdictional boundaries and whether such connections altered local opportunities. A border might raise transaction costs by separating legal systems or markets, while simultaneously creating advantages for retail services, tourism or specialised production. Integration could reduce one type of cost but expose a weaker local economy to stronger competitors. Theoretical renewal therefore involved specifying the mechanisms through which an international boundary mattered, rather than treating geographical proximity as either a handicap or a source of prosperity. In the Czech setting, the same frontier could be a commercial resource, an ecological corridor, a political symbol and an obstacle to access to a hospital.

Milan Jeřábek's contribution to the debate was to place the borderland within the larger process of Czech regional differentiation. His 2000 examination of the borderlands and regional development asked how the position of peripheral territories should be evaluated when their external relationships were being reorganised. The argument was not simply that formerly closed regions had become open. It concerned the uneven conversion of an altered geopolitical position into sustainable regional advantage. Local transport, the composition of the economy, institutional competence and the relationship between a settlement and its regional centre could reinforce or weaken the opportunities associated with cross-border contact. The article helped establish borderlands as a distinct field of systematic geographical enquiry rather than a collection of local descriptions. It also connected research carried out for practical regional policy with a more general question: how can a state understand territories whose functional relationships extend beyond its own administrative and statistical system?

Jaroslav Dokoupil addressed the conceptual problem from the perspective of the Czech–Bavarian frontier. His 2000 study examined theoretical models of border situations and tested their relevance to a landscape whose physical continuity had long been divided by incompatible political arrangements. The analysis distinguished the border itself from its changing consequences, showing why an opening could transform some activities more readily than others. A road link might facilitate travel while educational qualifications or planning procedures remained subject to national rules. The study also emphasised that theoretical categories must be adapted to the historical situation of particular borderlands. An account built for a frontier between established Western European market economies could not be transferred without qualification to an area emerging from state socialism. This work

made the language of border effects more precise and helped Czech researchers formulate hypotheses capable of being compared across different parts of the country.

The subsequent article by Dokoupil and Tomáš Havlíček in 2002 examined how the terms border and border region should be identified and delimited. Their contribution is significant because it treated definition as a research problem rather than an administrative preliminary. The influence of an international boundary depends on the nature of the interactions being studied, and the same area can belong to different functional border regions for different purposes. A labour-market boundary might extend much farther into the interior than a zone affected by daily shopping, while a landscape-management partnership could follow a mountain ecosystem instead of an economic catchment. Defining an area by what the border does, rather than only by where it lies, strengthened the methodological basis of comparative studies. It also cautioned against equating all areas adjacent to a state boundary with peripheral territories. A frontier can separate major development corridors as well as sparsely populated mountain landscapes.

Pavel Chromý introduced a complementary historical-geographical perspective. In his 2000 study of the delimitation and analysis of borderlands, he argued that present regional characteristics could not be explained without reconstructing the earlier boundaries that organised settlement, administration and identity. A contemporary international line is only one boundary among several that may have left a geographical imprint. Former ethnic divisions, the area affected by post-war resettlement and the zone once subjected to Cold War restrictions do not coincide exactly. Their effects may persist in patterns of population stability, civic participation, landscape maintenance and local perceptions of belonging. Chromý's approach invited researchers to assemble historical sequences instead of treating a single date as the origin of the present. For planning practice, it offered a further warning: a development proposal designed for an apparently empty or marginal area may encounter cultural and ecological relationships created long before the project was conceived.

Martin Hampl's analysis of differences among Czech border regions added an important comparative qualification. His 2000 article showed why contrasts between borderland and interior could be less pronounced than disparities between individual border regions themselves. Population concentration, industrial inheritance, links to metropolitan centres and trajectories of restructuring produced substantial internal diversity. This finding challenged the political temptation to regard the whole frontier as a single disadvantaged territory requiring uniform treatment. The industrial towns of the northern border could not be evaluated by the same criteria as mountain villages in the south-west or the Czech–Slovak corridor. Nor could a border project's success be inferred solely from the amount spent in a region. The relevant comparison was the change in its opportunities relative to the structure and needs of the locality. Such work linked political-geographical enquiry to a broader Czech tradition of studying regional hierarchies and spatial differentiation.

The first issue of Geografie in 2000 became a particularly revealing snapshot of this emerging field. Its contributions approached the Czech borderland through theory, historical development, political behaviour, agricultural land use, demographic change and the perception of neighbouring communities. Rather than offering a single disciplinary definition,

the collection demonstrated the benefit of combining political geography with economic, social and historical geographical methods. An electoral analysis asked a different question from a study of settlement change, but both investigated the endurance of territorial divisions. A local survey could reveal uncertainty or mistrust concealed by national statistics, while a regional typology situated those reactions within longer processes of development. The publication also marked a transition in scale. Borderlands were no longer represented exclusively as a diplomatic question settled between capitals; they appeared as places where the actions of municipal governments and the interpretations of inhabitants helped determine whether new opportunities would be realised.

A Czech–Saxon case study by Jeřábek, Kateřina Kučera, Bernhard Müller and Jan Přikryl made this local dimension especially clear. Published in 2000, the research compared perceptions of socioeconomic change in Kraslice and Klingenthal, towns connected by proximity but shaped by different political and economic histories. The study formed part of a wider international project examining the borderland as a space of mediation. Responses from local residents exposed the uncertainty accompanying political opening and economic restructuring, as well as uneven readiness to cooperate. Such observations complicated an account that equated partnership agreements with integration. People might welcome more opportunities while retaining doubts about a neighbouring labour market or the prospects of their own town. The findings also drew attention to the asymmetry of social expectations: a shared frontier was experienced from two sides that did not necessarily attach the same meaning to wages, development or mobility.

The Elbe/Labe Euroregion offered a further setting for examining cooperation beyond a single pair of towns. Established during the early phase of post-socialist rapprochement, its activities connected local and regional authorities in northern Bohemia and Saxony through projects in infrastructure, culture, environmental management and institutional exchange. Jeřábek's 2002 study of Czech–Saxon cooperation described the interplay between the European scale of funding arrangements and the local scale at which individual projects were designed. The distinction was crucial. A funding programme could create an opportunity, but a municipality still needed a partner, administrative knowledge and a project capable of producing benefits on both sides. The research did not reduce Euroregional activity to expenditure totals. It asked how programmes altered the networks through which local authorities recognised shared problems, negotiated priorities and learned to work with institutions operating under different rules.

The creation of Euroregions across the Czech frontier was among the most visible institutional changes of the 1990s. The Neisse–Nisa–Nysa Euroregion had already emerged in December 1991 at the meeting point of the Czech, German and Polish territories, illustrating that local cooperation could begin before Czech independence. Subsequent associations linked municipalities and regional actors along the German, Polish, Austrian and Slovak borders. Their organisational forms differed, but they commonly sought to make the frontier less divisive through cultural encounters, planning discussions, tourism initiatives, transport improvements and small community projects. These groupings were not replacements for states or new tiers of sovereign government. Their importance lay in creating working structures

where people responsible for neighbouring territories could speak regularly rather than communicate solely through national administrations. Geographers treated this development as an institutional experiment whose consequences depended on participation, continuity and the balance of resources between partners.

The geography of a Euroregion did not necessarily correspond to the geography of everyday interaction. An association could cover a broad territorial area while its strongest contacts were concentrated in a few municipalities or organisations. Conversely, informal networks could link employers, schools or households across a border outside the projects recorded by a formal institution. This distinction became important when evaluating European integration. The number of registered members, meetings or approved applications documented institutional activity but could not by itself establish the existence of an integrated cross-border region. Researchers therefore began to distinguish administrative cooperation from functional integration. The latter required evidence of sustained mobility, service exchange, social contact or joint problem-solving. It was possible for a Euroregion to function successfully as a project organiser without eliminating the legal, linguistic and economic obstacles that structured the daily choices of residents. That limitation was not necessarily a failure, but it changed the standard against which achievements should be judged.

European financial instruments supplied both resources and a new vocabulary for this work. During the pre-accession period, Phare cross-border cooperation programmes helped support projects at the Czech frontier, while INTERREG operated on the European Union side. After Czechia entered the Union in May 2004, the integration of funding arrangements made cooperation an increasingly regular part of regional policy. Later programming periods introduced more detailed requirements for partnership, eligible expenditure and the demonstration of effects across the border. These procedures encouraged municipalities, universities and non-profit organisations to move from occasional exchanges towards planned, documented cooperation. Yet they also imposed administrative burdens, particularly on small communities with limited staff. From a geographical perspective, the distribution of project capacity became a subject in its own right. Areas with experienced institutions could more readily secure funding, potentially reproducing a difference between well-connected border towns and places facing greater need but possessing fewer organisational resources.

The Czech Republic’s accession to the European Union in 2004 was therefore an important transition, but it should not be mistaken for the disappearance of border controls. Membership changed the legal and economic framework of interaction, including customs arrangements and access to common policies, while checks on people continued until Czechia joined the Schengen area on 21 December 2007. The distinction between the two dates matters for any account of border permeability. Entrepreneurs and local authorities were adapting to the European single market before travellers experienced the wider removal of routine controls at land crossings. Researchers examining changes in mobility had to identify which regulatory barrier was actually being reduced and when. They also needed to consider new forms of administrative separation that remained after accession, including social insurance, taxation and professional qualifications. The frontier was transformed by successive changes, not erased in one institutional event.

The 1997 Czech–German Declaration on Mutual Relations and Their Future Development gave the western border a different kind of political setting. Agreed in Prague on 21 January, it recognised the burdens of the twentieth-century past while establishing a framework for cooperation oriented towards the future. The Czech–German Fund for the Future and associated dialogue arrangements supported encounters and projects that could address practical needs without requiring agreement about every historical interpretation. For border communities, the declaration opened a channel between high-level reconciliation and local activity: schools, cultural organisations and historical associations could meet across a frontier still marked by the memory of war and expulsion. This mattered geographically because trust and shared knowledge affected the willingness to engage in projects. A road crossing could be opened by administrative decision; restoring relationships around a former village, monument or cemetery demanded a more patient process of mutual recognition.

Czech–Bavarian cooperation developed where physical and historical obstacles reinforced one another. The Šumava and Bavarian Forest constituted a connected mountain landscape, but access routes and settlement patterns were unevenly distributed. Tourism and protected-area management created possibilities for shared interpretation of scenery and ecosystems, while different administrative responsibilities complicated common action. The boundary between a Czech national park and protected areas on the German side did not remove the ecological continuity of forests, watercourses or wildlife habitats. Equally, a conservation proposal might affect employment and mobility differently in Czech and Bavarian villages. Geographers studying this region therefore had to consider the politics of landscape as well as the politics of transport. Environmental cooperation could give the borderland an international profile, but it could also bring disputes over permissible tourism, forest interventions or local development. A shared environment did not guarantee identical priorities among the authorities responsible for it.

The Czech–Saxon frontier presented a contrasting pattern of industrial settlements, historic trade routes and densely connected valleys. In some localities the border cut across closely related economic spaces; elsewhere mountain terrain channelled contact through a small number of passes. Industrial restructuring after reunification and the collapse of state-socialist production systems reshaped employment on both sides, although not at the same speed or under the same policy conditions. Cross-border shopping, subcontracting and commuting developed against disparities in income and living costs. Research on the Elbe/Labe region and the towns of Kraslice and Klingenthal highlighted the need to distinguish these short-term exchanges from institutional cooperation aimed at longer-term regeneration. Border openness could expand a town’s functional hinterland without providing the resources required to renew declining industry. The comparative study of local perceptions was therefore not supplementary to economic analysis: it helped explain the expectations and social relationships within which development initiatives operated.

The Czech–Austrian frontier was shaped particularly strongly by the previous division between Eastern and Western Europe. In the south of Bohemia and Moravia, opening the boundary restored possibilities for visiting nearby towns, managing shared landscapes and creating transport links interrupted during the Cold War. The border nonetheless passed through

extensive rural and relatively sparsely settled areas, so improvements in legal accessibility did not always overcome distance to employment and services. Towns such as České Velenice and Gmünd offered examples of proximity complicated by separate municipal and administrative systems. Agricultural differences, tourism and the management of river valleys provided other fields for cooperation. Researchers found reason to ask whether stronger international relations were helping local centres connect to broader regional economies or merely increasing movement through them. The route from an individual crossing to sustainable settlement development depended on investment and the quality of local public services as much as on the withdrawal of a border barrier.

Along the Polish boundary, the geography of contact was particularly varied. Mountainous sections of the Sudetes limited transport options, whereas divided or neighbouring towns offered opportunities for intensive daily exchange. The Těšín/Cieszyn area retained a multilingual historical inheritance and social networks whose development long preceded European integration. In Český Těšín and Cieszyn, the line dividing one urban fabric made the relationship between state boundaries and functional urban space immediately visible. Residents could share commercial, cultural and familial connections while using different educational, legal and administrative systems. Elsewhere, cooperation across the Czech–Polish border was organised around tourism, mountain rescue, rivers and transport corridors. These differences discouraged the use of a single Czech–Polish model. The research question was less whether the frontier had opened than which combinations of settlement form, institutional capacity, history and infrastructure allowed a recognisable cross-border community to develop.

The Czech–Slovak border followed a different trajectory because the two states had recently belonged to the same federation. The division of 1993 required new arrangements for administration and international movement, yet common language practices, professional links and family networks softened many of its social effects. Economic restructuring created differences in employment and wages that could influence the direction of commuting, but these differences should not be attributed to the border alone. The frontier traversed rural mountain districts and connected transport corridors, each possessing distinct capacities for interaction. In the White Carpathians and the Beskids, environmental and cultural initiatives could draw upon a shared landscape and historical relations, while local governments had to operate within separate national systems. After both countries entered the European Union in 2004 and Schengen in 2007, researchers could examine a particularly revealing sequence: the creation of a new state boundary followed by the gradual removal of several barriers to crossing it. This sequence showed that political demarcation and social separation were not equivalent processes.

The evolution of Czech cross-border policy also changed the role of local government. Municipalities that had previously directed most external matters towards central state offices could develop sustained relationships with neighbouring councils, although their legal powers remained defined nationally. Regional self-government, strengthened around the turn of the millennium through the operation of fourteen higher territorial units, added another level of potential coordination. The allocation of responsibilities became especially important for

transport, schools, emergency services and spatial planning. A town could express a desire for a cross-border bus route without controlling the permits, contracts or subsidies needed to operate it. Researchers consequently approached cooperation as a form of multi-level governance. An effective initiative might require residents, a municipality, a regional authority, national regulators and a European programme to act in compatible ways. Success depended not only on good relations between mayors but also on the distribution of competence across several institutions.

The European Grouping of Territorial Cooperation offered a legal instrument intended to address some of these coordination problems. Established under European legislation in 2006 and subsequently adjusted, the EGTC framework allowed participating public bodies from different countries to create an organisation with legal personality for agreed territorial tasks. It represented a further step beyond informal networks or project-specific agreements, although it could not override the statutory powers of its members. The TRITIA grouping, registered in 2013, linked regional authorities in the Czech, Polish and Slovak space and made the ambitions of cross-border coordination visible at a larger territorial scale. Its setting encompasses industrial, urban and mountainous territories with different economic trajectories. The instrument illustrated both the attraction and the difficulty of institutionalising cooperation. A new legal entity could sustain a joint agenda, but the practical integration of transport systems, labour markets or public services continued to depend on national rules and political commitment.

The relationship between cross-border cooperation and economic development required particular care in evaluation. Projects encouraging visitors to explore a shared historical landscape might benefit hospitality businesses without significantly reducing unemployment in disadvantaged districts. Improved roads could attract investment while increasing out-commuting to stronger centres across the border. Joint marketing might give small settlements a recognisable international identity, yet the firms capturing the largest share of expenditure could be located outside the participating area. Geographers examined such indirect effects by connecting the location of projects to settlement hierarchies, regional labour markets and accessibility. They also considered the counterfactual question of what might have happened without assistance. When a project area was already becoming more prosperous, rising visitor numbers alone did not establish the project’s causal contribution. The geographical value of evaluation lay in its ability to separate the effects of location, pre-existing development and newly created cooperation rather than treating every visible improvement as evidence of European funding success.

Environmental risks brought another dimension to the governance of borderlands. Rivers do not alter their behaviour at a jurisdictional line, and large floods can move rapidly through catchments shared by several states. Cooperation on the Elbe and its tributaries connected Czech and German institutions through information exchange, warning procedures and long-term river management. Mountain ecosystems faced comparable problems concerning forests, biodiversity, tourism and the management of protected land. Yet environmental boundaries seldom coincided with administrative ones. A programme organised within a Euroregional territory might cover only part of a catchment, while decisions on land use

upstream could affect communities outside its jurisdiction. Researchers increasingly recognised that the geographical scale of a problem must guide the territorial scale of cooperation. This insight also applied to air pollution and wildlife corridors. Cross-border partnership was most convincing when its institutional form followed the processes being managed, instead of simply assembling activities because they were situated near an international boundary.

Transport infrastructure gave a more immediate indication of the frontier's changing practical role. In the 1990s, routes inherited from periods of restricted movement could leave neighbouring towns connected by circuitous journeys, despite a short distance on the map. Upgraded roads, restored crossings and more coordinated public transport reduced some of these costs. However, the existence of a road was not equivalent to an accessible service for people without cars. Differences in ticketing, operating subsidies and timetables could make a cross-border journey difficult even after routine passport checks disappeared. Researchers could therefore measure accessibility through travel time, frequency and cost, rather than through straight-line distance. The political decision to permit crossing was necessary but insufficient for a functioning cross-border public transport network. The transport perspective also exposed variations between strong international freight corridors and weak local links, which often crossed the same national frontier but served very different users.

Everyday cross-border mobility gradually became an important source of evidence about the depth of integration. Travelling for work, education, shopping, healthcare or recreation produces overlapping geographies, each influenced by its own rules and incentives. A household might shop weekly in a neighbouring country but never consider living or working there. A commuter could cross a national boundary daily while remaining socially attached to a home municipality that faced economic decline. The distance and frequency of these journeys mattered, but so did their purpose and durability. Informal contacts often escaped official statistics, and recorded crossings were not always sufficient to reveal whether residents had developed a shared sense of place. Studies therefore combined quantitative observations with interviews and accounts of local experience. The resulting picture was often more selective than the language of a borderless Europe suggested. Different kinds of border crossing could increase at different speeds and even move in opposing directions.

Cultural and linguistic differences were similarly resistant to simple assumptions. Czech and Slovak speakers could often communicate directly, but local institutional conventions still required understanding. Czech–Polish contact had areas of linguistic familiarity as well as differences, while Czech–German and Czech–Austrian cooperation frequently placed greater weight on translation and language education. The presence of bilingual signs or public events demonstrated willingness to communicate, yet language competence varied by generation and social background. Historical narratives could also differ substantially among nearby communities, especially where population displacement, national disputes or old stereotypes remained part of family memory. Effective cooperation depended on the capacity to acknowledge such differences without treating them as immutable. Geographers and related social scientists paid growing attention to how identity, memory and personal contact influenced institutional projects. Their findings showed why shared marketing materials could

not substitute for the relationships needed to maintain a partnership after a funded programme had ended.

Research on political behaviour revealed that the history of the borderlands could matter even when residents were not participating in cross-border projects. Petr Daněk's 2000 examination of political culture compared electoral behaviour in areas with different post-war migration histories, using parliamentary election results from the 1990s. The geographical question concerned whether the historical distinction between borderland and interior retained measurable social and political consequences. Such work did not presume that every borderland inhabitant shared a particular political attitude. It investigated spatial variation in behaviour and assessed whether migration history offered an explanation alongside other local characteristics. Later studies developed this approach through the idea of phantom borders: historical lines that no longer operate as formal jurisdictions but remain visible in present social differences. This enlarged the study of frontiers from the actions of border guards and international organisations to the long geographical memory embedded in population structures and local institutions.

The concept of a phantom border acquired a more rigorous empirical basis in the 2020s. Matěj Korčák and Pavlína Netrdová examined the former Sudetenland boundary in a 2022 study of contemporary socio-spatial differentiation. Using detailed municipal information, they explored whether indicators connected with identity, social stability and human capital changed across a historical division that had disappeared from the formal political map. Their work treated an inherited boundary as a hypothesis to be tested rather than a line whose influence was self-evident. In 2024, Netrdová, Korčák and Vojtěch Nosek refined the cartographic approach through local-scale statistical mapping and analysis of spatial variation in border effects. The innovation was methodological as well as historical. It demonstrated that former political boundaries could be investigated with contemporary geographical tools, while the uneven strength of their effects cautioned against drawing conclusions from national averages alone.

The Schengen experience was examined directly in an international volume edited by Tomáš Havlíček, Milan Jeřábek and Jaroslav Dokoupil, published as a Springer book in 2018. Its chapters addressed the changing European context, development in border areas, Euroregions and the practical meaning of the Schengen arrangements. The volume consolidated a substantial Czech research tradition while opening it to a wider readership. Importantly, its central problem was not limited to whether border controls had been abolished. The contributors considered how the reduction of controls affected the functions of border regions, what new opportunities emerged and which asymmetries persisted. They distinguished political integration from lived experience and showed why residents might evaluate the effects of Schengen differently according to locality or occupation. The book also placed Czech cases in the wider Central European setting, where different frontiers had experienced distinct sequences of opening, state formation and economic restructuring.

The practical achievements of European territorial cooperation became increasingly diverse after 2007. Successive programming periods extended funding for shared cultural heritage, innovation, environmental protection, emergency preparedness, education and transport. On

the Czech side, the five cross-border programmes for 2021–2027 corresponded to partnerships with Poland, Slovakia, Austria, Bavaria and Saxony. This arrangement followed both national boundaries and the separate regional responsibilities within Germany, confirming that the geographical organisation of European cooperation did not always match a simple map of neighbouring states. Projects could be designed around a shared mountain range, a network of schools or a technological problem that required institutions from different territories. A crucial development was the gradual movement from symbolic gestures towards specialist working relationships. At the same time, project management became more demanding, and scholars continued to ask whether these structures could maintain cooperation outside the periods in which European grants were available.

The COVID-19 pandemic revealed the fragility of arrangements that had come to be regarded as ordinary. In 2020, restrictions on movement across internal European borders disrupted cross-border commuters, family visits and local businesses, including communities that had built their routines around frequent travel. Hynek Böhm's 2021 study of the Czech–Polish frontier examined the shift from debordering to renewed restrictions through several functions of cross-border cooperation, including governance, development, reconciliation and European integration. Rather than treating the emergency as merely an interruption to a linear process, the research demonstrated the political reversibility of everyday openness. The subsequent study of the Neisse–Nisa–Nysa Euroregion by Böhm and colleagues investigated how institutions responded and what resilience might mean for border communities. The experience made a geographical point with unusual force: the costs of closing a frontier are distributed unevenly, and those who depend most on daily crossings do not necessarily possess a strong voice in decisions taken by national governments.

An evaluation published in 2023 by Böhm, Artur Boháč and Łukasz Wróblewski brought three decades of experience into a single comparative enquiry. Their research asked whether Euroregions operating along Czechia's borders had become genuinely functioning cross-border regions, and proposed examining projects alongside working groups and the ability of institutions to confront persistent barriers. The approach distinguished the capacity to obtain and administer funding from the broader task of constructing durable cooperation. Research published in 2025 by Böhm, Tomáš Bendl, Boháč and Emil Drápela added a further perspective by using mental mapping to study the spatial practices of young people in the divided town of Český Těšín/Cieszyn. Where an institutional evaluation revealed how organisations operated, the maps of young residents offered evidence of the spaces they actually used and imagined. Together, these studies made the frontier visible at two complementary scales: as an arena of political organisation and as part of the everyday geography of a new generation.

By the end of 2025, Czech border research had become a sustained contribution to the wider field of political geography. Its most durable lesson was that legal openness, institutional cooperation and social integration are related but distinguishable processes. Borderlands that had once been understood mainly as remote national margins could be studied as sites where European policy, regional development, local identity and transnational networks met. Yet the research also documented the endurance of historical divisions, continuing disparities in resources and the possibility of renewed controls. The Czech experience therefore offers no

simple story in which one political boundary gradually loses all importance. It shows instead how the significance of borders changes according to the activity under examination, the institutions involved and the scale of observation. The resulting scholarship has sharpened the analysis of geographical regions themselves: territories are not defined only by administrative lines, but also by the connections, discontinuities and remembered histories through which their inhabitants organise their lives.

Electoral Geography, Territorial Organisation and the Spatial Dimensions of Political Behaviour

The electoral map of the Czech Republic has never been a simple reduction of political life to the colours of parties. It has recorded the restructuring of work, the movement of households, the persistence of historical differences and the changing capacity of local communities to organise political representation. After the establishment of the independent state in January 1993, geographers and researchers working at the boundary of geography, sociology and political science gained an unusually rich field of observation. Competitive elections could be compared across municipalities whose settlement patterns, religious traditions and economic histories differed substantially. The changing territorial administration of the state simultaneously created new levels at which political decisions were taken. Czech electoral geography consequently developed along two connected lines: an examination of where votes were cast and an investigation of how territory, institutions and everyday social environments helped to produce those votes. The distinction matters because a map can show an association between a locality and a political preference without establishing why its residents voted as they did.

The starting conditions were marked by an abrupt restoration of competitive politics after 1989 and by the gradual separation of the Czech and Slovak political arenas. The elections of 1990 and 1992 belonged to the preceding federal transition, yet they remained indispensable reference points for research after 1993. They documented how political pluralism was first expressed within a social geography inherited from industrial socialism, collectivised agriculture and the development of large housing estates. In the independent republic, the formation and consolidation of the party system allowed scholars to ask whether support for the principal political orientations would acquire stable territorial bases. The answer could not be obtained by looking only at Prague or at national vote shares. It required local electoral returns to be placed alongside information on education, employment, occupation, age and settlement type. The subsequent availability of detailed official results turned a succession of national contests into evidence concerning the changing spatial organisation of Czech democracy.

One of the defining characteristics of this research environment was the exceptional fragmentation of local government. Czechia retained more than six thousand municipalities, many containing only a few hundred inhabitants, and these communities continued to elect

their own councils. Such a fine-grained territorial system generated an exceptionally detailed electoral record, but it also demanded care in interpretation. A municipality of seventy residents and a city district with tens of thousands of inhabitants were both administrative observations, although their social processes, electoral competition and statistical reliability differed markedly. A comparison that gave each municipality equal weight could tell a different story from one that weighted observations by the electorate. Researchers therefore had to distinguish between spatial units as places of political life and spatial units as containers for statistical data. The proliferation of very small units made the Czech case valuable for studying neighbourhood effects, local candidates and persistent differences in turnout, while increasing the risk of mistaking local chance for a general territorial pattern.

Tomáš Kostelecký provided a particularly important bridge between geographical training and electoral research. His early academic work examined the geography of elections as a constituent part of political geography; later investigations at the Institute of Sociology of the Czech Academy of Sciences brought municipal election results into a sustained programme of regional and local studies. Rather than regarding party support as an isolated political indicator, these investigations compared results with changing social structures and the spatial consequences of post-socialist transformation. They developed an analytical language in which the composition of a locality's population could be separated from influences associated with living in that locality. This also established a productive relationship between the discipline's institutional settings. University geography departments contributed theories of spatial differentiation and methods of cartographic analysis, while sociological research groups brought survey evidence and models of electoral behaviour. Some of the strongest Czech achievements arose precisely where those approaches were combined.

The first decade of the independent republic presented researchers with several electoral geographies at once. Support for market-oriented parties was often stronger in prosperous urban settings and in localities with more highly educated and professionally mobile populations. The traditional industrial regions, including parts of north-western Bohemia and northern Moravia, frequently offered a different political environment, one shaped by restructuring, unemployment and the declining security of industrial work. Rural differentiation was equally significant. Agricultural districts, suburbanising villages and small settlements with strong religious institutions did not constitute a single electoral category. Political competition also changed during the decade, complicating any attempt to assign a permanent ideological identity to a territory. A locality's position in the map of a particular election could reflect a durable social structure, a candidate's popularity, the strength of a local organisation or the temporary salience of an economic issue. Geographers increasingly treated electoral stability as something to be demonstrated, not assumed.

The institutional design of parliamentary elections supplied another reason to consider territorial scale. Deputies were chosen through proportional representation, but the division of the country into constituencies and the method of converting votes into seats changed over the study period. Until 1998, eight electoral regions were used; from 2002, parliamentary contests were organised in fourteen regions corresponding to the higher territorial self-governing units. These districts varied considerably in their numbers of voters and seats. An

identical percentage obtained by a party in two regions could therefore have different implications for representation, especially under the former allocation formula. The electoral geographer had to distinguish the spatial distribution of preferences from the separate, rule-governed process through which preferences became parliamentary mandates. Without that distinction, an apparently geographical explanation of unequal representation could conceal an effect generated by district magnitude or electoral arithmetic.

The creation of fourteen self-governing regions in 2000 was a fundamental change in the geography of Czech public authority. Earlier arrangements had combined districts and a highly fragmented municipal layer, whereas the new regions acquired elected assemblies and responsibilities associated with regional development and public services. The district offices ceased their functions at the end of 2002, and from January 2003 many administrative competences were exercised by municipalities with extended powers. These changes produced overlapping territorial frameworks: fourteen political and administrative regions, eight larger NUTS 2 cohesion regions used for statistical and European policy purposes, and smaller functional areas organised around everyday service centres. For political geography, the reform raised questions about legitimacy, regional identity and accessibility. Citizens might identify strongly with a historical region without recognising the boundaries of a new administrative unit; decisions affecting schools or transport might be taken at a level not obviously connected to their immediate municipality. Electoral evidence could help trace the consequences, but could not by itself establish whether the new territorial institutions worked effectively.

Regional elections beginning in 2000 opened a distinct arena of political competition. They did not simply reproduce national parliamentary contests on a smaller map. Regional candidates had to appeal to voters concerned with hospitals, transport, secondary education and the management of regional resources, while national parties tried to translate broader political identities into regional mandates. At the same time, the degree of mobilisation differed from that in elections perceived as determining the national government. Differences in turnout could thus alter the electorate as well as the ranking of parties. In a region with an ageing population, smaller towns and substantial travel distances, campaigning conditions differed from those in the Prague metropolitan hinterland. Analysis of regional voting required an understanding of the powers of the institutions being elected and the local availability of political organisations. A single map of victorious lists would reveal little about the relationship between the territorial reform and citizens’ effective participation in regional government.

The Czech Senate offered an alternative electoral geography because its members were elected individually by majority vote in single-member constituencies. The upper chamber consists of eighty-one senators serving six-year terms, with one-third of the seats normally contested every two years. A candidate can win in the first round by obtaining an absolute majority; otherwise the leading candidates proceed to a second ballot. Consequently, the geography of senatorial elections is a geography of candidates, districts, second preferences and varying participation as much as one of parties. The division into eighty-one constituencies is not equivalent to either municipal borders or the fourteen parliamentary electoral regions. Researchers comparing senatorial results with lower-house elections need to account for the

timing of each contest and for the fact that most of the country does not vote for senators at every senatorial election. An especially strong local candidate may succeed even where the candidate's party performs relatively weakly in national elections.

The first direct presidential election in 2013 created a further nationwide electoral contest with a different political logic. Before that reform, presidents had been elected by parliament; afterwards, voters chose between candidates in a two-round process. The presidential elections of 2013, 2018 and 2023 became especially useful for examining regional variation in the appeal of individual political figures, the transfer of support between rounds and the role of turnout in a contest structured around personalities. A presidential map cannot simply be read as a map of permanent party loyalties. The candidates' biographies, campaign messages and perceived relationships to the political establishment may attract combinations of voters that parliamentary parties seldom unite. The second round additionally invites strategic decisions by people whose preferred first-round candidate has been eliminated. Czech research has therefore used presidential contests to extend questions of electoral geography beyond parties and to study how institutional rules mediate the territorial expression of political preferences.

The municipal level remained distinctive because local political competition was frequently organised outside nationally established parties. Independent candidates and local electoral lists were prominent in many small communities, where personal acquaintance and practical reputations could matter more than national ideological labels. The use of open-list proportional arrangements, the limited number of council seats and the small size of many electorates produced a form of political geography closely tied to social networks. A voter might support a neighbour responsible for a successful cultural association while choosing a different political party for the Chamber of Deputies. Such behaviour should not be understood as ideological inconsistency. The issues, candidates and expected consequences of the two elections differ. Czech studies of local government have shown how the prominence of independent lists affects mobilisation and electoral competition, with the composition of local political supply becoming a geographical characteristic in its own right.

The relationship between municipality size and political participation became a major analytical question. In smaller settlements, candidates and councillors were more visible, the stakes of local infrastructure decisions could be immediately felt, and informal communication sometimes substituted for professional campaigns. Large cities offered a much wider range of political alternatives but could also increase the social distance between residents and representatives. These circumstances helped explain why local-election turnout often differed systematically between small municipalities and major cities. Nevertheless, size alone was insufficient. The extent of political competition, recent conflict over development, municipal financial conditions and the age structure of residents could all change participation. Researchers comparing local-election data from 1994 onwards tested whether the spatial distribution of turnout remained stable despite changes of national government and local leadership. The persistence of some participation clusters suggested that electoral involvement had a territorial history that no single campaign could explain.

A geographical analysis of turnout must also account for what participation measures. The proportion of registered voters casting ballots is affected by eligibility, registration

arrangements, residence patterns and the particular institutions being elected. Students living away from their registered municipality, residents commuting daily across an administrative boundary and citizens temporarily abroad may encounter different practical conditions of voting. Local elections and elections to the European Parliament do not have identical electorates or rules, while Senate contests occur only in selected districts. Comparisons across these elections therefore require more than placing turnout percentages in adjacent columns. Low turnout may reflect dissatisfaction, weak competition, the perceived remoteness of an institution or obstacles associated with individual circumstances; aggregate returns cannot discriminate among these explanations without supporting evidence. Treating abstention as a uniform political opinion would be especially misleading in regions containing communities with contrasting demographic and mobility profiles.

Membership of the European Union from May 2004 introduced yet another electoral scale. Czech voters began electing members of the European Parliament, whose constituencies and political stakes differed from those of local or parliamentary elections. European elections provided an opportunity to examine whether attitudes towards supranational governance displayed the same territorial structure as domestic political preferences. They also exposed the role of mobilisation: in the 2024 European Parliament election, national turnout was 36.45 per cent, while the Prague figure was substantially higher and participation in Karlovy Vary and Ústí nad Labem regions was markedly lower. These differences cannot be attributed solely to attitudes towards Europe. Education, age, campaign intensity, party competition and general participation habits are also distributed unevenly in space. The European electoral level expanded Czech electoral geography by adding a political institution that was spatially present in the national territory yet not organised through the same governing hierarchy as Czech parliamentary and municipal authorities.

The growth of suburban settlements after 1993 provided a particularly revealing case of the relationship between residential mobility and political behaviour. Families moving from Prague, Brno and other cities into surrounding villages often brought educational profiles, occupational positions and political experiences that differed from those of longer-established residents. A suburban municipality might therefore change its parliamentary preferences even if the political convictions of individuals remained unchanged. Kostelecký's 2005 study of political behaviour in four Czech metropolitan areas between 1990 and 2002 explored this transformation through municipal typologies, turnout and local socio-economic characteristics. The importance of such work lay in identifying a demographic mechanism behind an electoral shift. Yet the arrival of new residents could also change local debates about schools, roads, building permissions and public space. In that second process, the character of the place itself was altered, and electoral change could no longer be reduced to the addition of households with particular incomes or education levels.

Praha's changing electoral hinterland demonstrated why metropolitan political geography could not stop at the administrative city boundary. Commuter flows linked growing suburbs to the capital's employment market, while electoral participation remained organised by municipal residence. New housing estates beyond the metropolitan boundary thus became part of the capital's functional urban region without being subject to its municipal institutions.

The consequences included disputes over transport provision, infrastructure finance and land-use planning between neighbouring authorities. In national elections, such localities frequently resembled prosperous metropolitan neighbourhoods more than the rural districts to which they had historically belonged. In local contests, however, they retained the political institutions of villages or smaller towns. This divergence between functional integration and administrative fragmentation helped explain why apparently similar populations might encounter different political choices depending on the level of election. It also demonstrated the limits of territorial categories based entirely on the formal status of a municipality.

Brno and its surrounding South Moravian settlements supplied a related but not identical setting. The city combined universities, specialised services and a changing technology economy with a hinterland containing towns and villages of distinctive cultural traditions. The importance of religion in parts of Moravia complicated an interpretation of voting based exclusively on income and occupational structure. Christian democratic political traditions retained local significance in some areas even as the national party system became more volatile. Elsewhere, expanding residential districts brought younger households with different priorities concerning transport, schools and the environment. Geographers who compared Brno with Prague could therefore distinguish features shared by metropolitan areas from those resulting from a particular regional history. Similar questions arose around Plzeň and Ostrava, although their industrial composition and suburban development differed. The Czech network of urban centres offered several contrasting settings in which to examine whether metropolitan status had a common electoral effect.

Electoral differences across the rest of Czechia were closely associated with the uneven geography of economic transformation. The restructuring of mining, heavy industry and manufacturing affected the everyday prospects of communities in different ways and at different moments. In parts of the Ústí nad Labem and Moravian-Silesian regions, persistent unemployment and lower educational attainment helped shape the social environments in which political choices were made. The relationship was not mechanically deterministic: voters experiencing similar economic hardship could support different parties, abstain or respond primarily to particular candidates. Nevertheless, the concentration of deprivation in specific districts meant that national political debates about employment, welfare and economic security had an uneven territorial basis. Studies of the spatial dimension of Czech transformation connected electoral geography to this broader social polarisation. They showed that the changing location of advantage and disadvantage was relevant to understanding why the same national political message resonated differently in metropolitan and peripheral settings.

The historical boundary of German-speaking settlement before the Second World War offered a more challenging explanation for contemporary electoral distinctions. Large-scale displacement and population replacement after 1945 profoundly altered the social composition of many border districts. After 1989, the territorial consequences of that history remained observable in settlement structures, local institutions, property relations and patterns of collective memory. Martin Šimon’s investigation of ‘phantom borders’ examined whether former historical divisions could still be detected in electoral behaviour decades after

the population changes that had transformed the regions. The use of historical geographical information systems and carefully aligned electoral data made it possible to trace the older boundary without treating it as an existing political border. A historical correlation, however, did not prove that people were consciously voting in response to a pre-war division. It invited investigation into the institutional and demographic processes through which an earlier boundary might continue to influence present conditions.

Research drawing on long electoral time series added a second historical dimension. In the monograph published in 2014 on voting patterns from 1920 to 2006, Kostelecký, Renáta Mikešová, Markéta Poláková, Daniel Čermák, Josef Bernard and Martin Šimon compared evidence from democratic elections separated by major changes of regime. The purpose was not to assume an uninterrupted political culture through the decades of dictatorship. It was to investigate how far territorial patterns reappeared, what kinds of social structures might account for them and which apparent continuities dissolved on closer inspection. Historical evidence made the question of stability more demanding. A similar vote share in the same district at two dates could conceal different populations and political organisations, particularly in areas affected by displacement or urbanisation. The comparison therefore required knowledge of the relevant historical units, settlement changes and differences among party systems. It showed the potential of electoral geography to contribute to historical sociology without reducing contemporary behaviour to inherited regional stereotypes.

The companion 2015 work on parliamentary election results from 1992 to 2013 provided a more concentrated account of the post-socialist period. Drawing on the exceptionally detailed data available for Czech municipalities, its authors mapped the shifting geography of parties that had entered representative institutions and tested explanations rooted in population composition and regional context. A sequence of maps was especially valuable because it allowed readers to see a party's changing electoral footprint rather than its fortunes at just two national totals. A party might lose substantial votes everywhere while retaining its relatively strongest support in a recognisable group of municipalities; alternatively, a modest national change might conceal a major movement between metropolitan and rural areas. These are different kinds of electoral change, and a single countrywide percentage cannot distinguish them. The publication also demonstrated how a historical atlas of results could serve as an instrument of causal enquiry when its spatial patterns were linked to demographic and economic evidence.

One central methodological issue concerned the distinction between compositional and contextual explanations. A compositional interpretation attributes territorial electoral differences to the characteristics of the people living in each area: education, occupation, religious affiliation, age or other measured attributes. A contextual interpretation asks whether features of the local setting have an additional influence, through social interaction, institutions, shared experience or the visibility of political alternatives. Josef Bernard and Kostelecký developed a conceptual account of local and regional context in a 2014 study, distinguishing mechanisms that can too easily be grouped under a vague notion of 'place effects'. Bernard, Kostelecký and Šimon tested contextual interpretations in detailed municipal data in the geographical journal Geografie. Their findings indicated that some

territorial patterns were not fully explained by compositional variables alone, although unequivocal identification of neighbourhood influence remained difficult. The resulting caution was itself a methodological achievement: geographical variation deserved explanation, not automatic conversion into a claim that place determines belief.

This problem is connected to the ecological fallacy, which became increasingly important as maps and municipal datasets were combined. An electoral district with a high proportion of university graduates and a high vote share for a particular party does not establish that the graduates themselves supported it. The voters within each territorial unit are heterogeneous, and their individual choices are not observed in aggregate results. Statistical relationships may change when researchers combine small municipalities into districts or divide a large city into wards, a difficulty commonly described as the modifiable areal unit problem. Spatial autocorrelation creates a further challenge because nearby municipalities are rarely independent observations. Their housing markets, labour flows, social networks and media environments may overlap. Czech studies increasingly used spatial regression, local indicators and other geographical techniques to examine such structures. The strongest analyses combined methodological sophistication with an explicit statement of what the available evidence could and could not reveal about individual motivations.

The role of neighbouring communities illustrated both the attraction and the limitations of contextual analysis. Residents of adjoining villages may work in the same factory, attend the same school and read the same local news despite voting in separate municipalities. Conversely, two neighbourhoods within a city may have different housing tenure, social networks and patterns of contact. The boundary drawn around an observation can therefore misrepresent the social space in which political views develop. Researchers studying contextual effects had to ask whether the appropriate exposure was the municipality, a commuting area, a historical region or a smaller neighbourhood. They also had to consider whether an electoral pattern resulted from interactions among residents or from the selective movement of people already sharing similar preferences. Without longitudinal or individual-level evidence, the two mechanisms could look alike on a map. This concern encouraged collaboration among electoral geographers, survey researchers and specialists in spatial statistics.

By the 2010s, party-system change provided a test of the durability of Czech electoral territories. Earlier competition had been organised to a considerable extent around established parties of the centre-right, the social-democratic left, Christian democracy and the Communist tradition. The growing influence of ANO 2011 and the appearance of new or reorganised formations changed the labels attached to those broad divisions. The parliamentary election of 2013 marked a significant disruption of older balances, while subsequent contests showed that a party’s disappearance or decline did not necessarily erase the social geography of its former supporters. Researchers thus distinguished continuity of underlying regional differences from continuity in party organisations. The electoral map could remain socially stratified even when names, coalitions and campaign styles changed substantially. This insight helped connect post-socialist electoral history to wider debates over political realignment, but the Czech case also demonstrated that local culture and the

changing supply of candidates must be considered alongside broad class or educational divisions.

The decline of the Czech Social Democratic Party provided an especially informative case study. Having long been one of the principal electoral organisations, the party gradually lost its capacity to draw together a sufficiently broad territorial electorate and failed to enter the Chamber of Deputies in 2021. Spatial research of its trajectory could identify whether support disappeared evenly or retreated into particular localities, including some with older industrial or left-wing traditions. The meaning of such a decline differs from that of a party whose support was originally concentrated within a small number of municipalities. A study published in the Journal of Maps used spatial statistics and a sequence of electoral maps to follow changes in social-democratic support during parliamentary elections from 2006 to 2017. Its central methodological lesson extended beyond that party: political change should be examined through the redistribution of support in space, not simply through the national rise or fall of electoral shares.

The changing geography of radical-right voting required a similarly long perspective. Jonáš Suchánek and Jiří Hasman's 2023 analysis followed populist radical-right electoral support between 1992 and 2021 and distinguished earlier organisations from the newer Freedom and Direct Democracy movement, SPD. This was necessary because parties classified under a broad political family can attract different social and territorial electorates in successive decades. The study identified both substantial differences and increasing convergence between parts of the older and newer support patterns. It interpreted some persistent concentrations through the idea of places experiencing abandonment or perceived political neglect. The authors' analytical approach was geographically important because it avoided presenting every manifestation of radical-right voting as the product of one unchanging electorate. Instead, it asked how local grievances, the decline of established representation and the evolution of political rhetoric interacted across regions and over time.

The language of 'left-behind places' brought electoral geography into closer contact with regional-development research, but it also required precision. A peripheral municipality is not defined by a single economic indicator, nor are all its residents politically discontented. Places can be disadvantaged by the withdrawal of public services, poor transport connections, declining population, limited employment options or repeated failures of local institutions to secure investment. The electoral consequences depend on how these problems are perceived and represented, as well as on the alternatives available on the ballot. Some communities respond with strong civic organisation, local independent lists or a preference for established parties; others may turn towards challengers or abstention. The geographical contribution lies in distinguishing these pathways rather than describing an entire region as resentful. Such an approach allows historians of post-socialist transformation to connect electoral behaviour with the material development of places without asserting that economic deprivation inevitably produces any one political outcome.

The parliamentary election of 2021 presented researchers with an unusually clear opportunity to compare national political realignment with territorial continuity. Two major electoral coalitions, SPOLU and the alliance of Pirates and Mayors, competed against ANO and other

parties for the leadership of the country. The aggregate result brought a change of government, but the regional patterns did not become entirely new. A 2022 study by Jakub Lysek and Karel Macků argued that established socio-spatial divisions continued to shape the outcome, even as the political organisations competing across them changed. Their analysis considered the influence of local religiosity, economic structure, political leadership and other contextual characteristics rather than treating the entire state as one uniform contest. An explanatory map had to distinguish the relative electoral success of coalitions in metropolitan and prosperous areas from the distribution of support in less successful industrial and peripheral districts. The study exemplified a mature phase of electoral geography in which dramatic national events became occasions to test established hypotheses against new political configurations.

The 2021 election also coincided with a significant change in the electoral law. In February of that year the Constitutional Court found elements of the previous formula for allocating parliamentary seats incompatible with constitutional requirements of electoral equality and proportional representation, although it did not abolish the division into fourteen electoral regions. The subsequent legislative amendment changed coalition thresholds and introduced a two-stage system for distributing mandates, involving an initial allocation within regions and a further calculation at national level. For historical comparison, this matters because electoral results are composed of at least two analytically distinct objects: votes cast by citizens and seats awarded under the rules in force at the time. A shift in the composition of the Chamber may partly reflect the different translation of votes into mandates, independently of any change in municipal political preferences. Czech political geography therefore had to attend to constitutional design and electoral mathematics alongside the socio-economic circumstances of the voters.

The 2021 outcome also warned against equating an electoral coalition's vote with a single coherent social group. SPOLU brought together parties with different historical roots and local areas of support, while the Pirates and Mayors alliance linked electorates shaped by contrasting organisational traditions. At municipal level, the distribution of preferences for a coalition could conceal the persistence of distinctive religious, metropolitan or local-government traditions among its constituent supporters. Similarly, the geography of ANO combined people of different ages, occupations and political histories. Such diversity cannot be recovered from aggregate coalition totals alone. Preferential voting, candidates' regional visibility, survey data and the longer history of the participating parties are needed to produce a more complete account. This methodological qualification is important when analysts describe election maps as evidence of a confrontation between two Czechias. The opposition between broad territorial blocs may be visible, but the people within those blocs and the relationships among their political concerns remain far more varied.

The direct presidential elections offered an additional perspective on political alignments that could cross parliamentary boundaries. In 2023, the second-round contest between Petr Pavel and Andrej Babiš illustrated how a nationwide choice could simultaneously mobilise metropolitan, rural and regional loyalties. Research published by Pavel Maškarinec in 2025 analysed strategic voting across the presidential elections of 2013–2023, drawing on the results within administrative districts of municipalities with extended powers. These

microregional units provide a useful compromise between the instability of very small municipal observations and the loss of detail caused by analysing only the fourteen regions. The study's focus on strategic voting emphasised the choices made when the field narrows after a first ballot. In such a system, the geographical distribution of votes between rounds cannot be explained by a simple transfer of fixed party blocs. The composition of the available alternatives, expectations about which candidates can win and changes in participation all matter.

The 2025 parliamentary election supplied a further endpoint for evaluating continuity and change within the period covered by this book. Official results recorded national turnout of 68.95 per cent and victory for ANO with 34.51 per cent of valid votes and eighty of the two hundred seats. SPOLU received 23.36 per cent and fifty-two seats, while STAN, the Pirates, SPD and Motorists also entered the Chamber. ANO led the count in thirteen of the fourteen regions, with SPOLU finishing first in Prague. These facts make the geographical scale of electoral interpretation especially important. Victory across thirteen regions does not mean that each municipality contained the same political majority, or that the size of ANO's advantage was uniform. The capital's contrasting result also does not establish a homogeneous metropolitan electorate. Researchers must look beneath the regional summaries to municipalities, neighbourhoods, turnout differences and the distribution of second-placed parties before deciding how the apparent national polarisation was structured.

A contemporary geographical appraisal of the 2025 election by Radim Pileček and David Totka drew attention to the relationship between economic dissatisfaction, differences among settlements and the relative stability of Czech political polarisation. Such work is valuable at the end of a long historical investigation because it offers a comparison with the political map of the early republic without assuming that the same parties or issues had persisted throughout. The contemporary opposition between some prosperous urban settings and poorer industrial or peripheral territories echoed earlier findings about social differentiation, yet the party organisations expressing those differences had changed considerably. Moreover, a national map could hide exceptions: smaller towns with strong local leadership, rural municipalities with relatively high incomes, and urban neighbourhoods affected by deprivation. Recognising these exceptions helps avoid the mistaken inference that a geographical tendency is a universal territorial law. The historical task is to explain why broad patterns recur while the politics of particular places continues to evolve.

Differences in turnout in 2025 made the electoral geography still more complex. The official regional figures showed participation above seventy-one per cent in Prague, Central Bohemia and several other regions, whereas Karlovy Vary and Ústí nad Labem remained close to sixty or sixty-two per cent. Regional vote totals therefore reflected not only party choice among participants but also unequal mobilisation of eligible electorates. A political group might achieve a large share of ballots cast in a place with low participation without representing a comparable proportion of all eligible residents. For analysis of representation, it can be useful to show both party votes as a share of valid ballots and as a share of the eligible electorate, with the difference explicitly explained. However, even those measures cannot reveal the intentions of non-voters. This distinction between electoral success and the social reach of

participation became increasingly relevant when Czech researchers studied disengagement, trust and the changing meaning of political belonging in less advantaged territories.

Geographic scholarship also investigated the organisation of political competition at the local level rather than concentrating solely on broad electoral cleavages. Petr Voda's account of local elections in a fragmented municipal system described a political landscape in which independent and local lists were far more prominent than the national presence of parliamentary parties might suggest. Work by Bernard, Kostelecký, Zdenka Mansfeldová and Mikešová subsequently examined the relationship between independent lists, turnout and the competitiveness of local contests. Their findings indicated that independent participation could mobilise voters while also encouraging organisational changes through which national parties retreated from some municipal arenas. These findings are not contradictory. Local autonomy can strengthen participation while, under certain conditions, reducing the number of distinct electoral competitors. The relevant question is what political choices remain meaningfully available to citizens and how local reputations, social networks and institutional rules shape those choices. This research connected electoral geography to the functioning of democracy at the scale most immediately experienced by residents.

By the 2020s, quantitative methods had expanded the range of questions that could be asked of historical and contemporary election results. Global measures of spatial autocorrelation indicated whether similar turnout levels or party shares clustered across the country; local indicators helped identify particular concentrations and exceptions. Spatial regression could test whether a relationship varied between regions instead of imposing one coefficient on all municipalities. Historical GIS allowed researchers to align older boundaries with contemporary data, while interactive cartography made long election series easier to inspect. Yet the availability of sophisticated techniques did not remove the need for historical and substantive judgement. Census variables often changed their definitions, district boundaries were altered, political parties merged or disappeared, and electoral rules shifted. Responsible comparison therefore required the documentation of harmonisation decisions, attention to uncertainty and a willingness to acknowledge when a spatial pattern remained unexplained. Methods were useful because they made explanations more demanding, not because they could replace an understanding of Czech political history.

The achievement of Czech electoral geography between 1993 and 2025 was thus neither the discovery of an immutable division between cities and countryside nor the production of a sequence of attractive election maps. It was the construction of a research tradition capable of examining political change at several territorial scales and across several generations of voters. The local record of municipal returns provided an empirical foundation; the reform of territorial administration and the diversification of electoral institutions widened the questions; and cooperation among geographers, sociologists, political scientists and statisticians sharpened the methods of explanation. The resulting scholarship showed that social composition, historical inheritance, local institutions and political campaigning can all contribute to electoral differentiation, but that none acts independently or everywhere in the same way. The political geography of modern Czechia consequently offers a broader insight

into territorial democracy: election results emerge from the interaction of citizens, places and rules, and an adequate history must keep all three in view.

Geopolitical Change, Territorial Conflicts and Czech Research beyond Central Europe

The political map inherited by the Czech Republic in January 1993 offered an unusually revealing starting point for geopolitical research. The country had become sovereign through a negotiated dissolution, while other parts of post-communist Europe were experiencing violent struggles over the same questions of statehood, borders and national belonging. What appeared on an atlas as a sequence of newly drawn lines concealed markedly different histories of political authority. The Czech case supplied one example of an agreed constitutional separation; Yugoslavia, the Caucasus and parts of the former Soviet Union supplied others in which territorial claims were defended by force or sustained without international recognition. For geographers, these contrasts raised questions that an account of diplomatic events alone could not resolve. They had to distinguish the location of a frontier from the ability to administer it, the geographical extent of a political community from the identity claimed on its behalf, and a state's recognised area from the territory effectively governed. From 1993 onwards, Czech research increasingly approached such questions through the relations between political power and geographical space.

This development should not be described as the simple revival of an earlier national school of classical geopolitics. The discipline emerged into a world where traditional explanations based on position, resources and military access were being challenged by research into discourse, identity, political economy and the social production of territory. Nor did every Czech study of international politics become a contribution to political geography merely because it concerned a distant country. A specifically geographical contribution examined how distances, spatial configurations, borders, territorial institutions, networks and place-based identities affected political outcomes. It could treat a military route as materially consequential while also asking how politicians represented that route as a threat. The two forms of explanation did not always fit comfortably together, and disputes about their relative value became part of the intellectual history of the field. By the end of the period, Czech scholars had explored both the material distribution of power and the processes by which maps, classifications and geopolitical narratives acquired authority.

A significant point of consolidation came through collaboration between geography and international-relations scholarship. The Czech Science Foundation project on the political geography of the world, undertaken in 1998–1999 at Masaryk University with cooperation from Charles University, explicitly sought to bring neglected topics and contemporary theoretical approaches into Czech geographical teaching and research. Its published legacy included the 2000 volume Stát, prostor, politika, prepared by Petr Jehlička, Jiří Tomeš and Petr Daněk. The volume placed statehood, uneven global development and political organisation into a

common geographical frame. The importance of this effort lay less in the creation of a rigid canon than in the provision of a vocabulary with which students could compare very different political settings. Political borders could be studied beside development disparities and political institutions without assuming that one dimension accounted for all the others. Such a framework made global processes legitimate objects of inquiry within Czech human geography.

The former Yugoslavia remained an instructive reference point throughout the period, even as the research agenda expanded further east and south. Its dissolution showed that international intervention, population displacement and control of roads, towns and corridors could continually alter the practical meaning of territorial agreements. Bosnia and Herzegovina demonstrated the persistence of territorially differentiated political institutions after a formal peace settlement. Kosovo brought the distinction between self-determination and territorial integrity into especially sharp focus. The European recognition of Kosovo’s independence in 2008 subsequently became a reference point in debates about other secessionist territories, although the histories and legal circumstances of those cases differed profoundly. Czech research drew on these developments to examine the comparative problem of recognition rather than to treat each declaration of independence as evidence of equivalent statehood. The central question was how formal status interacted with effective administration, external sponsorship and a population’s relationship to its institutions.

A parallel theoretical discussion concerned the image of the world conveyed through geopolitical language. In 2006, the international-relations scholar Petr Drulák examined the tension between geopolitics and anti-geopolitics in Czech political thought. His work is particularly useful for a geographical history because it showed that interpretations of national position were not simply deductions from the country’s location in Europe. Narratives about belonging to the West, the dangers of dependence and the historical experience of domination shaped the significance attached to the same physical setting. These narratives could influence public arguments about alliances without making topography irrelevant. Geographers interested in critical geopolitics found here an invitation to investigate political images rather than accepting them as descriptions of objective necessity. A serious analysis of the Czech case had to ask who was authorised to speak for the nation, which historical analogies were repeatedly invoked and how regional identity entered discussions of global order.

The methodological challenge became especially explicit in Jan Kofroň’s research. His 2011 article in Geografie examined the distribution of military power after the Cold War, moving beyond general statements about the emergence of a unipolar world to consider the uneven capabilities of states. This was followed in 2012 by a historical analysis of the relationship between space and warfare. The latter distinguished the scale of tactical engagements from the wider strategic setting in which armies move, receive supplies and seek political objectives. Technical change had altered the distance over which force could be delivered, but it had not removed the need to occupy positions, cross obstacles or maintain lines of communication. For political geography, the argument was a reminder that the physical attributes of space remain relevant even when modern political conflict is understood through cultural and

institutional categories. Kofroň's work reopened a question sometimes marginalised in geographical discussions: how can material constraints be analysed without turning geography into destiny?

His intervention also identified an intellectual division between geography and international relations. In a 2012 study for Mezinárodní vztahy, Kofroň compared approaches treating space principally as a material setting with approaches emphasising its intersubjective construction. In his later examination of the fragmented field of political geography, published in 2017, the disagreement was linked to contrasting ideas of explanation, evidence and research design. Critical approaches could disclose how a territorial threat was represented, while more explicitly causal research might ask whether distance, force ratios or transport infrastructure affected the feasibility of military operations. Both questions were legitimate, but neither answer was a substitute for the other. Czech debate therefore developed around the possibility of methodological exchange rather than the simple victory of one school. This is an important feature of the national record: theoretical disagreement itself generated research questions, particularly when a subject such as war demanded both a study of perception and attention to material conditions.

In 2016 Kofroň carried that reasoning into a set of geostrategic scenarios for the Czech Republic. His article in Geografie drew on offensive neorealism to consider how European security might change if the United States withdrew from a central role on the continent. The scenarios were not predictions presented as inevitable events; they were conditional exercises that made the assumptions of a particular theory visible. Their geographical content included the location of the Czech Republic among larger powers and the consequences of different arrangements for deterrence and military access. Scenario construction also opened the analysis to criticism, since readers could question the premises and ask whether alternative alliances or institutional changes might alter the outcome. The wider achievement was methodological. Instead of equating geopolitics with authoritative pronouncements about an unavoidable national fate, the study offered a model whose theoretical foundations and implications could be scrutinised.

The study of European defence expenditure by Kofroň and Jakub Stauber, published in 2023, illustrates this development. Examining the reaction of European states to the conflict following 2014, the authors tested several explanations for differences in military spending. Geographical distance from Russia proved significant in their analysis, with measures based on road connections performing particularly well. The result was not a claim that one variable governed all defence decisions. It indicated that the route along which forces might actually move can convey information that the straight line between capitals omits. Their subsequent analysis of the division of NATO expenditure between personnel and equipment extended attention to the composition of military resources. Such research located geopolitics within a framework of explicit indicators and testable propositions. It differed from the rhetorical practice of attaching the word 'geopolitical' to any international disagreement.

Alongside military geography, the changing political map became a durable field of investigation in Prague. Martin Riegl's 2013 monograph on transformations of the political map after 1945 placed late twentieth-century developments within the longer history of

decolonisation, state dissolution and recognition. The approach was comparative: the proliferation of independent states did not mean that all political entities enjoyed identical sovereignty or that every territory seeking separation followed the same trajectory. Some achieved international recognition and joined existing organisations; others maintained institutions and borders without broad diplomatic acceptance. A third category operated with varying degrees of autonomy within recognised states. Riegl's work helped move Czech discussion away from an atlas-based assumption that political entities can always be divided cleanly into states and non-states. The variety of actual territorial arrangements required more careful concepts and case selection.

The distinction between effective independence and international recognition became particularly productive through Riegl's collaboration with Bohumil Doboš. Their comparative study of South Sudan and Somaliland, published in 2014, addressed two African territories that had followed sharply different routes towards sovereignty. South Sudan achieved international recognition in 2011 after a negotiated process, but subsequently experienced grave internal conflict and difficulties of state-building. Somaliland had developed governing institutions and a degree of security without comparable international recognition. The contrast challenged a linear account in which greater administrative effectiveness necessarily produces diplomatic success. The researchers examined external political conditions together with internal institutional development. A territory's position in international society could not be derived from a checklist of domestic features alone. For Czech political geography, Africa was thereby brought into a comparative argument about the state rather than treated merely as a remote setting for conflict.

The 2017 edited volume Unrecognized States and Secession in the 21st Century expanded this debate through contributions from Czech and international researchers. Edited by Riegl and Doboš, it assembled theoretical chapters and cases concerning recognition, national identity and the conditions under which secessionist entities survive. Its value lay in juxtaposing questions that are frequently conflated: whether an entity governs, whether it claims legitimate self-determination, whether external states support it and whether international recognition follows. Subsequent publications made this separation still more precise. The 2018 study on the decision-making of major powers treated diplomatic support as a factor requiring systematic comparison, while the 2019 examination of partially independent territories questioned the assumption that full sovereignty and complete dependence exhaust the possible statuses. The corresponding research programme enlarged the conceptual map on which disputes over independence could be placed.

The post-Soviet area offered a demanding test of these distinctions. Abkhazia, South Ossetia, Transnistria and the Armenian-controlled entity formerly operating in Nagorno-Karabakh differed in population, geography, patronage relationships and histories of armed conflict. Their political survival depended in varying degrees on forces outside the territories that they claimed to govern. One question was whether local institutions possessed independent authority or functioned primarily through external military and financial support. Another concerned the routes by which people, goods and information entered territories whose international status remained disputed. Such connections could sustain an administration

while also limiting its freedom of action. Riegl and Doboš's 2018 analysis of secession and Russian geopolitical strategy placed these entities within a regional system rather than interpreting each conflict in isolation. The role of Russia emerged as both an international actor and a spatially differentiated source of security, economic access and diplomatic leverage.

The University of Ostrava developed a complementary and especially detailed research tradition on the South Caucasus. Vladimír Baar, Tomáš Hoch and Vincenc Kopeček approached de facto statehood through political institutions, social relations and the history of conflicts. Their work often combined conceptual comparison with examination of the organisations and practices operating inside a disputed territory. This focus mattered because a place excluded from the principal structures of diplomacy does not necessarily lack political life. Elections, courts, civil organisations and informal networks may exist, although their independence, accountability and capacities differ markedly. The Ostrava studies therefore examined the internal political geography of entities that conventional international maps represent only as disputed areas. The question was not to endorse claims to sovereignty but to understand what forms of rule actually existed and how they were maintained.

Research on Abkhazia provides a clear example. Hoch, Baar and Kopeček examined the conditions under which democracy could develop in a de facto state, considering the use of democratic practices as a possible claim to legitimacy. A later study by Kopeček, Hoch and Baar in 2016 compared the governance of Abkhazia with political institutions in Nagorno-Karabakh and drew attention to the difference between written rules and informal practice. A formally established party, election or municipal office might have a role whose actual significance depended on personal networks and relations with a patron state. The problem could not be solved by importing institutional categories from a widely recognised parliamentary democracy without modification. In the Caucasian cases, understanding politics required knowledge of how the territory had been divided, which communities had been displaced and which external routes and resources sustained administration.

An even more direct link between geography and peace research appeared in studies of civil society and conflict transformation. The Ostrava researchers examined organisations operating in Nagorno-Karabakh and Abkhazia rather than treating negotiations between governments as the only setting in which peace could be shaped. Their 2016 research on Nagorno-Karabakh asked whether civil organisations could influence the attitudes and social relationships that continued to reproduce conflict. The 2017 study on Abkhazia similarly investigated the opportunities and constraints faced by civic actors in a territory lacking general recognition. Such work did not assume that the presence of a non-governmental organisation automatically indicated a path towards reconciliation. It showed that the political possibilities of civil society were conditioned by security arrangements, local elite relations and uncertainty about territorial status. Conflict transformation, in this perspective, involved more than redrawing boundaries or signing documents.

A subsequent development involved the material and symbolic role of places within conflicts that continued for decades. In 2023 Slavomír Horák and Tomáš Hoch examined the fate of sacred sites in Nagorno-Karabakh as evidence of the failure of conflict transformation. Religious buildings, cemeteries and monuments were not interchangeable points on a map.

They embodied claims of historical residence and cultural belonging, and they could become objects through which one population interpreted the intentions of another. Damage to such places or changes in access could intensify the insecurity surrounding a territory even where front lines were temporarily quiet. The contribution of this research was to join conflict studies with cultural geography without dissolving either into the other. An agreement about jurisdiction might address the recognised boundaries of authority, but the everyday geography of memory and worship could remain contested. Political geography consequently had to account for the meanings people attached to particular locations as well as for the locations themselves.

Events in Nagorno-Karabakh during 2020 and 2023 also showed why political-geographical classifications require continual historical revision. The 2020 war altered the territorial situation established after the earlier conflict, and Azerbaijan's military operation in September 2023 ended the existence of the separatist administration in the territory. The subsequent departure of much of its Armenian population transformed the human geography on which older descriptions had rested. A research article accurately identifying a functioning de facto institution in 2016 could therefore be historically valuable without describing the situation in 2025. Treating political entities as fixed map categories would obscure this change. Czech comparative studies offered tools for asking how the loss of a patron, a transport corridor or control of a particular settlement affected political survival, but the empirical answer had to be updated as events unfolded. The case underlined the difference between a durable conceptual framework and the changing objects to which that framework is applied.

Other research from Ostrava extended the geographical analysis of the Caucasus from secessionist administrations to the more ambiguous realm of informal politics. Kopeček's examination of Georgia's Javakheti region investigated how local political relations, ethnic composition and communication with the central state developed through institutions that were not always visible in a formal constitutional account. Work on Georgia's transport and port projects later drew attention to the strategic significance of infrastructure and to the influence that political actors may exert through apparently economic decisions. The location of a port such as Anaklia matters because it is an interface between domestic territory, Black Sea transport and wider Eurasian connections. Yet the implications of its development cannot be read off a coastline alone. They depend on investment, regulatory authority, relations with neighbouring countries and the political credibility of the institutions overseeing construction. This combination of geographical position and institutional analysis broadened Czech work beyond the most conspicuous territorial disputes.

The notion of the patron state was particularly helpful in comparing post-Soviet conflicts. External support can mean the presence of troops, direct financial transfers, transport access, diplomatic representation or control over infrastructure. These are different resources with different spatial consequences. A subsidy may maintain public services in a territory that has limited access to international markets; a military base may protect an administration while narrowing its choices; and a border crossing may make ordinary travel dependent on decisions taken outside the territory. Researchers therefore had to avoid treating dependence as a single measurable condition. The 2017 study by Vladimír and Barbara Baarová of the socio-economic

structures of post-Soviet de facto states addressed these constraints after Russia's annexation of Crimea and in the context of changing Eurasian economic relations. It showed why the economic geography of disputed places is inseparable from their political status. Statehood on the ground requires resources, not simply symbols and declarations.

A different relationship between political territory and international recognition appeared in research on the Horn of Africa. Somaliland's separation from the political system of Somalia offered an unusual case of institution-building in the absence of widespread diplomatic recognition. Work by Tomáš Hoch and Kateřina Rudincová in 2015 examined the strategies used to legitimise its claim to independent statehood. Rather than measuring legitimacy from a single external standard, they studied the arguments made by its representatives and the political circumstances in which those arguments operated. The case encouraged comparison between the aspirations of local communities and the preferences of regional organisations that generally defended inherited boundaries. It also demanded attention to the uneven control exercised by authorities across the territories they claimed. For Czech political geography, the value of the Somaliland case lay in revealing the limits of a binary political map: the absence of recognition was not equivalent to the absence of government, and the existence of institutions did not resolve the question of sovereignty.

Western Sahara introduced another variation in the relations between political claim and external power. It combined competing claims to sovereignty, long-standing displacement and the presence of a territorially separated political movement with diplomatic recognition by some states and opposition by others. Comparative work on recognition by Riegl and Doboš included the Sahrawi Arab Democratic Republic alongside Kosovo, Somaliland and Transnistria. The selection itself was methodologically significant: cases were chosen because they differed in the effectiveness of control and the configuration of outside support. The authors sought to explain why some secessionist entities achieved international recognition while others did not, with particular attention to the behaviour of major powers. In doing so, they treated recognition as an international political process rather than a mechanical reward for satisfying a set of domestic institutional criteria. The geographical question was where international interests, regional alignments and territorial conditions intersected to shape that process.

Czech research on violent non-state actors in Africa subsequently shifted attention from recognition to the distribution of coercive authority inside existing states. In the Sahel, armed organisations, state forces and local communities occupied different and changing positions across large areas. Roads, borderlands, pastoral routes and administrative centres influenced how violence spread and how governments attempted to respond. The 2021 study of state-building and jihadism in Burkina Faso by Eeben Barlow, Bohumil Doboš and Martin Riegl asked how state authority could be challenged beyond the capital and whether political control extended to the localities named on a national map. It did not reduce such conflicts to a struggle over a fixed frontier. Their geographical substance lay in the intermittent control of settlements, the use of corridors and the vulnerability of institutions whose nominal jurisdictions exceeded their practical reach. This perspective brought the geography of governance into closer conversation with contemporary security studies.

The Mozambique insurgency offered a further opportunity for comparison. The research published in 2024 by Barlow, Doboš and Riegl examined the territoriality of the armed movement active in Cabo Delgado. Its concern was not simply to locate incidents of violence but to interpret how control of land, movement through particular areas and the use of local resources affected the insurgency's political possibilities. An armed group can conduct attacks without creating the durable institutions required for the exercise of territorial authority. Conversely, control of a strategic settlement or route may temporarily allow it to regulate civilian activity and extract resources. Distinguishing these circumstances helps prevent the inflation of claims that a group has conquered or governed an entire region. The study continued a Czech research line in which the intensity of violence was only one element of a wider analysis of territorial control. Political geography became an inquiry into the everyday mechanisms through which armed power is exercised.

The presence of Russian-linked military organisations in Africa added an explicitly international dimension to this research. Doboš's 2024 analysis of the Wagner Group examined how its practices could be understood through different categories of non-state armed actors. The problem was complicated by the organisation's connections with Russian state power and by the varying arrangements under which it operated in African countries. An armed contractor, a paramilitary organisation and a criminal network may share some activities while possessing different sources of authority and accountability. Their geographical reach depends on agreements with governments, access to transport and extraction sites, and the ability to sustain personnel far from their origin. Analysis of these arrangements provided a more precise alternative to describing every overseas armed operation as a conventional military deployment. By 2025 Czech work on Russian practices in Africa was also exploring the historical and contemporary forms through which external powers seek influence beyond formal colonial structures.

A further route beyond Central Europe led through Central Asia. Slavomír Horák's research on Turkmenistan, post-Soviet state-building and authoritarian rule placed geopolitical questions within detailed knowledge of local political institutions. His publications addressed informal networks, the personalisation of power and the foreign relations of a country situated between competing Eurasian interests. Geography entered this research through the organisation of access, the changing significance of external routes and the political relationships created by infrastructure. Turkmenistan's position between the Caspian region, Iran, Afghanistan and the wider Central Asian system did not dictate a fixed foreign policy, but it constrained the alternatives open to its leaders. A political map could indicate potential connections; actual relations required evidence about institutions, investment and state decisions. The combination of regional expertise and geographical reasoning made the research more informative than general assertions about Central Asia as a crossroads of great powers.

Horák's study of Turkmenistan in Eurasian railway geopolitics, published in 2023, gave this spatial problem a particularly tangible form. Railway corridors are simultaneously engineering systems, economic investments and instruments of political connection. Their strategic value depends not only on length but also on gauge compatibility, border procedures, neighbouring networks, financing and the reliability of the states through which they pass. In a region where

landlocked countries seek external markets while attempting to manage relations with larger neighbours, the choice of a route can acquire importance far beyond the freight it initially carries. The study showed how research grounded in one country can illuminate the political geography of a whole network. It also resisted an overly simplified picture of corridors as instruments wholly controlled by distant powers. Local governments, technical restrictions and institutional histories affect whether a proposed link becomes a durable connection or remains an ambition on a map.

Central Asia also illustrated the contested relationship between autonomy and national territorial integration. Horák and Martin Lepič's 2025 study of the 2022 protests in Karakalpakstan examined how a proposed change affecting autonomy became connected to regional identity and political mobilisation in Uzbekistan. The geographical issue was not limited to the legal wording of an autonomous status. It concerned a political community associated with a particular region and the historical meanings attached to its relationship with a central state. Such episodes remind researchers that internal boundaries can remain salient even when they have no status as international frontiers. They may define expectations about language, representation and the legitimate exercise of power. Czech scholarship on this case extended the study of secession and self-determination into an enquiry about the conditions under which recognised autonomy is challenged, defended or reinterpreted. The comparison with other post-Soviet regions required attention to historical specificity rather than a universal model of territorial grievance.

In East and South-East Asia, a somewhat different body of Czech research examined the historical formation and contemporary use of geopolitical ideas. Lukáš Laš and Vladimír Baar's 2014 article on Japanese geopolitics during the imperial period drew on political discourse and geographical representations to investigate the construction of Japan's regional ambitions. The study was historical in its immediate subject, but it belonged to the development of Czech political geography after 1993 because it applied newer theoretical questions to the relationship between cartography, ideology and expansion. Its analysis distinguished local intellectual traditions from concepts borrowed from European geopolitics and traced how different ideas were mobilised in state projects. The relevance to contemporary research was methodological. A map of an imagined region might document a political ambition rather than an objectively existing geopolitical unit. Understanding it required examination of the institutions and arguments that had produced the representation.

This attention to imagined geopolitical regions was complemented by an empirical study of Czech perceptions of the outside world. In 2015 Přemysl Mácha, Tomáš Drobík and colleagues published an investigation of geopolitical ideas among the Czech public. It asked how people understood foreign countries and international relationships, rather than assuming that strategic classifications used by specialists were shared uniformly by society. Such work could draw on survey evidence and social categories to examine the relationship between perceived distance and measured geography. It opened a route between the study of official geopolitical discourse and the images through which ordinary citizens made sense of international events. The contribution was not to replace military or diplomatic analysis with opinion research. It was

to show that political imagination is itself distributed socially, and that a country's position on a map acquires different meanings through education, media, memory and experience.

The growing importance of the Indo-Pacific gave Czech political geography further opportunities to investigate how narratives of regional order shape territorial claims. Research associated with Laš explored Japan, East Asian regionalism and disputes represented through political and media language. A 2022 study with Simon Wellisch examined media discourses surrounding territorial disputes in Japan, continuing the interest in how competing claims are made intelligible to domestic audiences. Such arguments often invoke historical names, maps and memories, even when the practical dispute concerns fishing grounds, maritime zones or strategic access. The task for political geography is to separate the legal, material and symbolic elements without pretending that they operate independently. In this setting, Czech scholarship contributed less through the production of a new regional doctrine than through comparative methods applicable to places far beyond the country in which the researchers worked. It demonstrated how a relatively small research community could enter debates concerning a much larger geopolitical theatre.

The Middle East and adjoining regions offered a second setting in which territorial forms departed from the conventional image of a unified state. Border fortifications, contested sovereignty and the uneven control of territory complicated attempts to interpret security through formal frontiers alone. In their 2020 study of border hardening, Branislav Mičko and Martin Riegl used political theory to examine how physical barriers and the assertion of sovereignty interact in the Middle Eastern context. A wall or fortified boundary is a material structure, but its construction also communicates claims about political unity and the separation of communities. Its meaning may be disputed by populations whose everyday connections run across it. The research therefore joined the physical presence of a barrier with questions about the production of political order. It also showed how apparently classical concerns with territory and sovereignty could be reconsidered using a contemporary theoretical vocabulary.

The territorial practices of radical Islamist organisations became the subject of a more extended collaborative investigation. In their 2021 monograph, Doboš, Riegl and Jakub Landovský compared organisations operating across the Middle East, Africa and parts of Asia. Their analytical distinction between less territorially rooted groups and those exercising more enduring territorial control was especially useful. The ability to recruit supporters or conduct attacks across borders does not imply the ability to administer a district, collect revenue or provide services. Conversely, an organisation that governs territory acquires obligations and vulnerabilities not faced by a clandestine network. Comparing the Islamic State, Al-Shabaab, Boko Haram, the Taliban and other organisations required attention to differing histories and forms of political organisation; it did not mean treating their programmes or social environments as interchangeable. The geographical achievement lay in relating modes of violence to modes of territoriality, thereby turning a diffuse security question into a set of researchable spatial relationships.

These studies also helped clarify an important limitation in the familiar distinction between state and non-state power. Some armed groups act through transnational networks while

controlling no continuous area; others develop local administrative institutions; still others coexist with or receive support from governments. The political meaning of a territorial foothold consequently varies with the organisation that holds it and the population living there. The 2020 monograph New Middle Ages, by Doboš, proposed a wider framework for analysing political settings in which multiple forms of authority coexist. Its language of post-Westphalian geopolitics was not a claim that states had disappeared. It was an attempt to compare different territorial arrangements without assuming that every political actor operates according to the same institutional logic. The research drew attention to the limits of map conventions that reserve meaningful political agency for recognised central governments. In doing so, it connected the study of insurgencies with a general theoretical debate about sovereignty and world order.

One of the most distinctive extensions of this research programme concerned the geopolitics of outer space. Doboš's 2018 book Geopolitics of the Outer Space applied questions about material environment, strategic access and political competition to a domain that cannot be understood through terrestrial borders. His subsequent 2024 study of space colonisation considered future power relations around the Moon, Mars and smaller celestial bodies. The research remained speculative in its treatment of activities not yet undertaken, but it distinguished proposals and scenarios from observed developments. Physical conditions, launch capabilities, orbital routes and the distribution of useful resources were examined alongside legal and institutional constraints. This was not a conventional account of geographical research on Czech territory. Its significance for the history of the discipline was the extension of spatial reasoning into an emerging field where infrastructure, environmental limits and competing claims could shape future political arrangements. The example also revealed the importance of making hypothetical assumptions explicit.

Across these diverse cases, an important methodological continuity was the demand to separate the observation of territory from the interpretation of claims about it. An unrecognised administration's published map does not establish the extent of its effective control. A military organisation's declaration of responsibility for an attack does not demonstrate that it governs the area concerned. A railway proposal is not equivalent to a functioning corridor, and an opinion survey about another country does not describe that country's political institutions. Czech research drew strength from using evidence appropriate to each question: administrative documents for recognition strategies, institutional records for governance, field interviews for local political relationships, spatial datasets for mobility or violence, and archival texts for geopolitical discourse. The diversity of these materials made broad comparison possible only if their different limitations were acknowledged. This caution helped distinguish systematic political geography from a collection of illustrations chosen to confirm an existing worldview.

The period after the full-scale Russian invasion of Ukraine in February 2022 further exposed the need for carefully differentiated spatial analysis. The conflict raised questions about access to the Black Sea, the strategic value of transport corridors, the protection of infrastructure and the human consequences of displacement and destroyed settlements. For Czech scholars, it also brought a heightened demand for immediate public explanation of military developments.

Yet a fast-moving war does not automatically make a confident geographical forecast reliable. The position of a front line is evidence about control at a particular time, not proof of the political outcome of a conflict. Claims about the importance of distance and military routes must be tested against logistics, institutions, technological capabilities and the decisions of the actors involved. Work on European defence expenditure illustrated one way of responding to renewed political urgency with transparent comparisons rather than with unqualified geopolitical assertions.

By 2025, Czech research beyond Central Europe had therefore developed along several lines that were related without becoming identical. Studies of recognition investigated why territorial entities received different diplomatic treatment. Research on the Caucasus examined institutions, civil society, informal power and the lived consequences of territorial disputes. African comparisons questioned the territorial reach of recognised governments and the capacity of non-state actors to establish rule. Central Asian studies explored autonomy, infrastructure and the spatial organisation of authoritarian power. Work on Asian geopolitical imagination analysed the representations through which territorial projects were legitimised, while astropolitics extended questions of access and competition beyond the Earth's surface. These lines drew on different methods and were located in overlapping university departments and interdisciplinary networks. Their common achievement was to make the spatial dimensions of power explicit and open to empirical investigation.

The international reach of the field should not conceal its constraints. Research on a disputed territory may be limited by insecure access, political pressure on interviewees, changes in administration and the fragility of local archives. Statistics produced by an unrecognised government cannot automatically be treated as equivalent to those maintained by a recognised national statistical office. Research on war requires careful handling of geolocated events and of the uncertainty surrounding reports from contested areas. Cross-national comparisons often encounter inconsistent definitions of autonomy, military expenditure or political violence. At the same time, Czech scholars working from a European institutional setting must remain attentive to local interpretations that differ from the conceptual assumptions of their discipline. Addressing these problems is part of the scientific contribution, not merely a preliminary difficulty to be mentioned and forgotten. Claims about territory become more persuasive when the route from evidence to conclusion remains visible.

The broader historical significance of the period lies in the movement from a post-1993 concern with new borders and political transition to a richer account of contested territorial order. The Czech experience encouraged attention to the dissolution and reconstruction of states, but it did not confine later scholarship to the country's immediate neighbourhood. Through studies of the Caucasus, Africa, Central Asia, the Indo-Pacific and the geopolitics of space, researchers investigated problems that could not be resolved by the formal distribution of sovereign colours on a map. They asked how political authority is supplied with resources, represented to populations, defended militarily and accepted or rejected internationally. Equally important, they questioned their own theoretical instruments and the terms on which political geography should communicate with international relations. By the end of 2025, the field's most durable result was not a single geopolitical model, but a set of comparative

questions capable of connecting the material conditions of territory with the changing institutions and meanings of political power.

Major Achievements, Research Schools, Leading Scholars and Landmark Publications in Political Geography

The development of political geography in the Czech Republic between 1993 and 2025 is best understood through a set of questions that its researchers learned to formulate with increasing precision. Why did voters in neighbouring districts respond differently to the same political transition? How could borders that had ceased to exist continue to structure social life? What distinguishes a territory governed by an unrecognised authority from a state whose sovereignty is widely accepted? And how should a geographer investigate military power without reducing it to the size of a country on a map? The most important achievement was not the establishment of a single dominant school. Rather, a network of university departments and research institutes produced complementary approaches to territorial power, political behaviour, collective memory and international conflict. Their work brought Czech evidence into wider theoretical debates while making international concepts answerable to the particular history of the Czech lands.

The starting point was unusually demanding. The independent republic emerged in January 1993 with inherited universities, an established tradition of social and economic geography and a newly defined state territory. Its borders with Slovakia had just become international; its western and southern frontiers retained the memory of the Iron Curtain; and the territorial arrangements of public administration were still changing. Political geography had to recover a disciplinary vocabulary compromised in part by ideological uses of geopolitics during the twentieth century. It also had to respond to institutions and events moving much faster than academic classifications: competitive elections, privatisation, European integration and the conflicts associated with the dissolution of socialist federations. The changes within the field were inseparable from the reconstruction of political life itself.

An assessment of its achievements must distinguish disciplinary contribution from public visibility. A widely read atlas of international conflicts can improve geographical literacy without necessarily changing a research method; a narrowly focused article may transform the way an enduring boundary is measured. Likewise, a university syllabus can sustain a field over decades even when it attracts less attention than a monograph. Czech political geography advanced through all three kinds of work: systematic observation of political differences, construction and testing of explanatory arguments, and teaching that made unfamiliar approaches accessible to successive students. Journals, book series, research projects and doctoral training provided the continuity that individual publications could not secure alone. The most consequential research often crossed institutional borders, drawing on political science, sociology, history, environmental studies and international relations.

A first identifiable centre of renewal was the Faculty of Science of Charles University in Prague. Its Department of Social Geography and Regional Development offered a setting in which political questions could be connected to established studies of settlement, population movement, regional differentiation and the organisation of the state. Jiří Tomeš, Petr Jehlička and their collaborators helped demonstrate that the geography of politics did not consist merely of drawing lines between countries. Territorial institutions, international environmental negotiations, changing forms of sovereignty and the geographical consequences of globalisation all belonged within the subject. The Prague programme was especially important because it placed political geography in conversation with methodological developments in human geography elsewhere in Europe. It also linked graduate training to empirical research on a country undergoing rapid political and administrative change. The resulting tradition was neither exclusively quantitative nor exclusively interpretative; it asked researchers to make a clear connection between the scale of a political problem and the evidence selected to explain it.

The collaborative volume Stát, prostor, politika, published in 2000 under the editorship of Petr Jehlička, Jiří Tomeš and Petr Daněk, gave this renewal a tangible form. Its chapters addressed unequal global development, the politics of environmental protection, globalisation, international assistance, the organisation of states, electoral systems, political integration and the geographical analysis of war. Instead of presenting political geography as a collection of country descriptions, the book assembled problems that could be approached through political processes and spatial relationships. The contributors also disagreed in emphasis, an instructive feature rather than a weakness of the project. Different questions required different accounts of causation, from the persistence of colonial inequalities to the operation of electoral rules. For Czech teaching, the volume provided a conceptual bridge between conventional regional geography and political-geographical debates that had developed internationally during the preceding decades. Its significance rests both on its content and on the collaborative intellectual infrastructure it helped establish.

The book was associated with a research programme supported by the Czech Science Foundation at the end of the 1990s. This is important evidence of disciplinary development because a programme designed to introduce neglected theoretical and methodological questions could generate a publication that subsequently served as a common teaching reference. The participating scholars worked across Charles University and Masaryk University rather than within a single metropolitan department. The project treated political geography as a body of research in need of conceptual renewal, not simply as a new label for an old curriculum. This approach allowed the Czech academic community to discuss geopolitical processes without reviving the deterministic assumptions that had given earlier forms of geopolitics their controversial reputation. It also encouraged a comparison between international ideas and the observable organisation of Czech society. The achievement was institutional as well as intellectual: scholarly cooperation became a means of extending the subject beyond its original teaching locations.

Electoral geography provided one of the earliest and most durable bodies of empirical achievement. Tomáš Kostelecký approached the first post-communist elections as an

opportunity to investigate how political change was registered across territory. His work on the 1990 and 1992 parliamentary elections examined economic, social and historical determinants of voting patterns, rather than assuming that a map of party support explained itself. The distinction was fundamental. A concentration of votes in an industrial district might reflect occupational structure, political traditions, local economic uncertainty or several of these factors together. By comparing spatial distributions and plausible explanatory variables, the research began to turn electoral mapping into a discipline of hypothesis testing. The analyses also showed that the restoration of competitive elections created a new kind of geographical evidence: repeated, territorially detailed observations of political choices that could be compared with demographic and economic statistics.

Kostelecký's subsequent academic career illustrates the importance of institutions outside geography departments to the growth of political geography. Working at the Institute of Sociology of the Czech Academy of Sciences, he developed research on local and regional political behaviour, the formation of party systems and spatial inequalities. His geographical education remained central to investigations of political attitudes and democratic institutions, even when the resulting publications appeared in sociological rather than geographical venues. The Department of Local and Regional Studies became a place where fine-grained municipal evidence could be linked to broader questions of social structure and political representation. This crossing of disciplinary boundaries increased the reach of electoral geography but also dispersed its literature across different catalogues and journals. The institutional history therefore cannot be written solely from the output of university geography departments. Some of its most sustained research programmes operated precisely at the meeting point between geography and another social science.

The two major collective electoral monographs of 2014 and 2015 marked a new stage in the maturity of this research. Koho volí Vaši sousedé?, written by Kostelecký, Renáta Mikešová, Markéta Poláková, Daniel Čermák, Josef Bernard and Martin Šimon, connected interwar parliamentary elections to the political patterns observable after 1989. The study did not claim that a party in one historical period was identical to a later party carrying a similar label. Instead, it used comparable political orientations and carefully specified geographical units to explore persistence and change. Its central question concerned whether regional voting differences resulted entirely from the composition of local populations or whether places themselves carried longer political histories. The analysis helped rescue electoral geography from a narrow preoccupation with one election at a time. Political preferences could now be examined as a changing territorial record, with both continuity and discontinuity requiring explanation.

Geografie výsledků parlamentních voleb, issued by the Institute of Sociology of the Czech Academy of Sciences in 2015, extended this enterprise through a systematic account of parliamentary voting between 1992 and 2013. The authors assembled detailed cartographic material and related electoral outcomes to characteristics of municipalities and their residents. Its value lay in the combination of an accessible geographical record with a framework for exploring explanatory factors. Repeated national elections could be compared without treating every change in party name as the disappearance of an underlying political

orientation. Maps made distributions legible; statistical comparisons tested whether the distributions were sufficiently stable or distinctive to justify further interpretation. The monograph also opened a route from specialised research to a wider readership interested in the politics of its own municipality. In this respect, the discipline gained both methodological depth and public relevance, without surrendering the distinction between interpretation and prediction.

A further contribution of the electoral tradition was its attention to the scale of analysis. Municipal election results cannot simply be read as the preferences of every individual living within the municipality, and district totals can conceal variation among neighbouring settlements. Czech researchers repeatedly confronted this ecological problem because their sources were organised into administrative units whose boundaries, size and composition differed. Some studies used detailed local data to locate unexpected contrasts; others compared districts over long periods to establish broader regional structures. The work encouraged caution about straightforward explanations based on the contrast between cities and countryside or between the centre and periphery. Where suburbanisation had altered a municipality's population, past voting patterns could change without an equally direct change in its institutional history. Conversely, the persistence of electoral differences despite demographic change raised questions about contextual influences. Recognition of these limitations was itself a significant advance in the interpretative standards of the field.

The arrival of new generations diversified the analytical questions further. Dominik Kevický's systematic review of Czech and Slovak parliamentary electoral geography, published in Acta Universitatis Carolinae Geographica in 2021, examined the subjects, theoretical frameworks and methods that had actually been used in the literature. Its conclusion was not simply that the field had accumulated useful election maps. It identified a strong concentration on the causes of uneven party support and comparatively limited attention to turnout, representation and qualitative approaches. The review also found that many studies employed quantitative techniques without making their theoretical assumptions explicit. Such an assessment represented a distinctive kind of landmark publication: it subjected an established research tradition to examination through a transparent review procedure. By identifying neglected questions, it encouraged scholars to regard the research agenda as open to revision. A mature discipline must be able to analyse its own habits with the same care that it applies to the political behaviour of others.

The methodological consequences of this self-examination were substantial. Electoral geography could draw on spatial statistics, historical cartography, surveys, interviews and institutional analysis, but none of these instruments automatically supplied a causal account. The selection of a municipality or a region as the unit of comparison carried assumptions about the political processes operating within it. The interpretation of parties as ideological families made long-run comparison possible, yet also required judgement about continuity between changing organisations. Even a technically reliable electoral map had to be related to a theory of social cleavages, political mobilisation, neighbourhood effects or territorial belonging. Czech scholarship increasingly recognised the difference between demonstrating that a pattern existed and explaining why it persisted. Research on voter participation and local

political leadership offered opportunities for a richer connection between measured outcomes and the mechanisms through which people encountered political institutions. The strongest achievement was consequently not an isolated statistical innovation but a growing culture of methodological scrutiny.

Political geographers also demonstrated the importance of historical boundaries whose formal political significance had disappeared. The former German-speaking borderlands supplied a demanding test because their twentieth-century history involved wartime territorial claims, the expulsion of German populations and extensive post-war resettlement. Petr Daněk's investigation, Does exist a political culture of the Czech borderland?, published in Geografie in 2000, considered whether parliamentary voting differed between these territories and the Czech interior after taking account of selected population characteristics. The research offered evidence that territorial history could retain a measurable relationship with political behaviour long after the population had changed. Its value was not a simple assertion that all borderland residents thought alike. Rather, it exposed the need to separate the effects of historical settlement, contemporary social composition and political context. A geographical boundary could remain analytically relevant even when it no longer had a role in formal administration.

Daněk's research also illustrates the bridging function of Masaryk University in Brno. His work connected cultural regionalisation, local democratic institutions and regional differences in political preferences. The 2002 study Geografické a strukturální předpoklady demokratické místní správy v pohraničí českých zemí extended attention to the conditions of local self-government in the Czech borderlands. This was a different kind of political geography from national electoral analysis. Its concern was with the social and territorial circumstances within which democratic administration had to operate after the political transition. In smaller communities, a formally identical set of municipal powers could operate under very different conditions of population stability, institutional capacity and historical continuity. The Brno perspective thus added an important warning against treating decentralisation as a purely legal process. Administrative arrangements could be examined as geographical institutions with uneven possibilities for local action.

The work of Pavel Chromý and colleagues at Charles University gave historical and cultural dimensions an equally important place in the field. Chromý's analysis of the delimitation of the Czech borderland, published in the special borderland issue of Geografie in 2000, showed why the term itself could refer to several different territorial realities. A state boundary, an area of post-war resettlement and a socially perceived periphery did not necessarily occupy the same geographical space. Later work with Michal Semian and Zdeněk Kučera treated regional identity as a process involving institutions, symbols and the experience of landscape. Although such studies are often classified as cultural geography, they are relevant to the territorial basis of political representation and mobilisation. They help explain why appeals to a historical region or a landscape may carry public meaning even where formal administrative borders have changed. This sustained attention to the social production of regions broadened political geography beyond the location of state power.

The Geografie issue devoted to borderlands in 2000 provides an unusually clear snapshot of collective research capacity. Milan Jeřábek examined the place of borderlands in regional development, Jaroslav Dokoupil addressed theoretical approaches to the Czech–Bavarian space, and another team investigated perceptions of development along the Czech–Saxon border. The same issue contained studies of historical delineation, voting behaviour and population change on the frontier with Austria. Together they demonstrated that no single measurement could define successful cross-border integration. The removal of a legal barrier might increase mobility while leaving differences in employment, public services and political trust. The publication also revealed collaboration among researchers whose interests ranged from economics to history and demography. For political geography, the achievement was an empirical approach to borders as complex territorial institutions rather than merely lines separating two jurisdictions. Its relevance grew as the Czech Republic prepared for and then entered the European Union.

Borderland studies subsequently had to contend with the altered meaning of the frontier itself. EU accession in 2004 and the implementation of Schengen arrangements at the Czech Republic's land borders in December 2007 reduced obstacles to everyday movement, but they did not erase differences in local government, language or collective memory. Czech geographers distinguished cross-border programmes and administrative cooperation from the more difficult question of whether people actually developed shared functional spaces. Euroregions became objects of study as organisations capable of supporting contacts without replacing sovereign jurisdictions. Research on commuting, local perception and regional planning provided opportunities to compare institutional intentions with territorial practice. In this sense, political geography helped make European integration intelligible at a scale below that of treaty negotiations. It demonstrated that the meaning of an international border could change even if its precise geographical location remained untouched. The research also supplied a historical baseline for understanding the temporary restoration of border controls during later crises.

An especially fruitful development emerged when the historical border question became a problem for spatial statistics. Matěj Korčák and Pavlína Netrdová examined the former Sudetenland boundary in a 2022 article in Geografie, using municipal-level indicators to investigate long-term socio-spatial differentiation. Their work did not presume that every observed difference originated in the post-war population transfers. Instead, it tested whether a discontinuity associated with the former boundary remained detectable when compared with other territorial patterns. That distinction made the concept of a phantom border empirically meaningful. The border was not treated as a mystical persistence of the past but as a possible historical factor reproduced, weakened or transformed by later institutions and population processes. Its significance depended on the variables studied and the scale at which their distribution was observed. Research of this kind connected historical geography with contemporary political questions through a method that could be examined and refined.

Pavlína Netrdová, Matěj Korčák and Vojtěch Nosek developed that approach further in a 2024 Journal of Maps article on measuring and mapping phantom borders at the local scale. Rather than offering a single coloured division between the former Sudetenland and the interior, the

paper used geographically detailed data and spatial statistical visualisations to explore variations in the strength of the boundary effect. Its maps made the uneven geographical persistence of a historical division visible, while also exposing limits in the conclusions that could be drawn. The achievement was the conversion of a familiar historical explanation into a set of testable spatial propositions. It showed how a regional legacy could be approached without assuming that an entire area remained socially uniform for generations. This offered a valuable contribution to international work on the political afterlives of vanished frontiers, while drawing directly on the unusually complex territorial history of Czechia.

Taken together, these studies identify an important Prague–Brno axis of scholarship rather than two wholly separate schools. Research on historical regions, voting, identity and borderlands moved between faculties, institutes and disciplinary traditions. Authors trained as geographers published in political science, sociology and history, and scholars working in those fields contributed concepts that geographers tested against territorial evidence. The shared intellectual problem was how to distinguish the political agency of institutions from the spatial inheritance of earlier events. Some projects emphasised longitudinal statistics and archival reconstruction; others explored the meanings that residents attached to boundaries and territories. Their results were not always directly comparable, because one addressed measurable differences and another explained meanings or experiences. Nonetheless, their coexistence prevented the discipline from becoming a technical exercise in cartography. It established political geography as the study of relationships between power and place across different historical periods and levels of social organisation.

Ostrava developed a different but complementary profile. The city's university tradition was situated in a region profoundly affected by industrial restructuring, yet its political-geographical scholars increasingly examined the organisation of states and nations far beyond the Czech Republic. An early landmark was Politická geografie, the 1996 university text written by Vladimír Baar, Petr Rumpel and Petr Šindler. Its publication supplied an accessible disciplinary framework when political geography was still being re-established in Czech higher education. The text was modest in length but important in function: it identified a coherent teaching subject and familiarised students with concepts that could be developed in subsequent research. Baar subsequently helped strengthen political and cultural geography within the university's academic programmes. The emergence of teaching and supervision across successive cohorts created a research environment that would later support comparative work on nationalism, unrecognised states and territorial conflicts. This institutional continuity gave Ostrava an influence not reducible to its geographical distance from the capital.

Baar's work on nations, ethnicity and political emancipation widened the intellectual foundation of the Ostrava tradition. His volume Národy na prahu 21. století: Emancipace nebo nacionalismus?, issued at the beginning of the new century, approached national movements as historical and political phenomena with distinctive territorial dimensions. The book was not restricted to the European state system: it invited comparison between claims to national self-determination, the institutional capacities of states and the geographical distribution of peoples. Such a framework proved useful when conflicts in the post-Soviet space raised

questions that conventional maps of recognised states could not resolve. National identity might provide a basis for political mobilisation, but it did not automatically determine the legitimacy or viability of an independent state. Distinguishing these dimensions became a characteristic concern of Ostrava political geography. It also prepared students for research requiring languages, historical understanding and direct engagement with societies affected by conflict.

A particularly significant achievement of the Ostrava research school was the systematic investigation of de facto states. Vincenc Kopeček, Tomáš Hoch and their colleagues studied political entities that exercised varying degrees of territorial control without obtaining general international recognition. This theme required geographers to work with categories ordinarily taken for granted: territory, government, sovereignty, citizenship and border. The difference between formal legal standing and effective local administration was not a semantic detail; it affected how schools, public institutions and civil associations functioned. By examining cases such as Abkhazia and Nagorno-Karabakh, the scholars challenged interpretations that reduced every unrecognised polity to an instrument of an external patron. Their analyses instead considered the interaction of local political institutions, historical claims, security dependence and international constraints. The resulting literature became relevant to comparative politics and conflict studies as well as to geography, showing how rigorous field-based work could make a Czech university a participant in a genuinely international debate.

The 2016 article De Facto States and Democracy: The Case of Abkhazia, published by Kopeček, Hoch and Baar in Bulletin of Geography. Socio-economic Series, illustrates this contribution. The researchers explored the claim that democratic practice might strengthen a de facto state's case for international recognition. Their investigation went beyond examining official statements and asked which conditions encouraged or obstructed political competition and institutional accountability within the territory. The relationship between external recognition and internal governance was shown to be neither automatic nor unidirectional. A movement could present democratic legitimacy as an argument while operating under severe security constraints and limited international contact. The study was significant because it approached a territory frequently described only through its diplomatic status as a political society with a functioning, contested institutional life. It thereby converted an apparently exceptional case into an opportunity for developing concepts of statehood that might also apply elsewhere.

Work on civil society brought another dimension to the Ostrava achievement. Tomáš Hoch, Vincenc Kopeček and Vladimír Baar examined conflict transformation in Abkhazia through field research, with the resulting article appearing in Problems of Post-Communism in 2017. Civil organisations were considered not simply as evidence of liberalisation but as actors operating within an unusual configuration of sovereignty, external dependence and unresolved conflict. The study questioned what space existed for voluntary groups when access to international institutions was constrained and relations with the internationally recognised parent state remained unsettled. Here the geographical approach lay in attention to the territorial and relational conditions of political action. Civil society did not exist in an abstract institutional environment; it worked across actual boundaries, restrictions and networks. The article helped

explain why models of peacebuilding developed for recognised states could not be transferred without modification to unrecognised political entities.

The edited volume De Facto States in Eurasia, prepared by Hoch and Kopeček and published by Routledge in 2020, was a landmark in the consolidation of this research. The book combined historical cases with contemporary analyses of the emergence, survival and potential failure of territories outside generally recognised statehood. It assembled authors concerned with the post-Soviet space, compared patron-client relationships and examined how local political orders functioned over time. Its structure made a theoretical point: a de facto state could not be adequately understood by examining secession alone. The circumstances of its formation, its institutional development and the reasons it might endure or collapse required separate explanation. The volume also demonstrated the international reach of research associated with Ostrava. The achievement was not simply that Czech scholars studied distant territories, but that their comparative framework invited other researchers to question established assumptions about what counts as a state in world politics.

These studies also revealed limitations inherent in researching disputed territories. Field access can be uneven; interviewees may face political risks; official statistics may reflect the interests of authorities seeking legitimacy; and the language used to describe territorial status can carry implicit political positions. The Ostrava tradition was valuable when it acknowledged these conditions as part of research design rather than hiding them beneath a supposedly neutral political map. An investigator needed to differentiate an authority's declaration from its administrative capacity, a claim to represent a population from evidence of popular support, and a foreign government's sponsorship from the internal choices of local actors. Comparative historical material could help place present conditions in context, but it could not eliminate the difficulty of changing facts on the ground. The most durable contribution was therefore a disciplined set of questions about effective control, political institutions and international recognition, supported by an expanding body of empirical case studies.

Prague meanwhile developed a line of geopolitical research that treated the material properties of space as relevant to international security. Jan Kofroň investigated military power and its distribution, the spatial character of warfare and the relationship between geography and international-relations theory. His 2011 study of the global distribution of military power, followed by work on space and war in 2012, argued that physical distance, terrain, technology and logistical constraints remained important even when political discourse appeared increasingly globalised. This was not a return to the claim that geographical position mechanically determines foreign policy. It was an argument that political geography loses explanatory capacity if it regards territory exclusively as a social representation. By examining how military capabilities interact with geographical conditions, Kofroň reopened a subject that had often been left to strategic studies. His contributions connected a long geographical concern with distance and location to contemporary debates about security and state behaviour.

Kofroň's methodological articles made this line of research especially distinctive. In 2012 he examined qualitative case studies as a possible tool for generating and testing general explanations, while warning that useful research designs depended on explicit epistemological

choices. In 2017 his Shattered Spaces of Political Geography, published in Acta Politologica, addressed the mutual neglect between political geography and political science. Rather than treating disciplinary separation as a harmless matter of terminology, he asked why scholars facing similar problems sometimes dismissed one another's methods. His response included greater attention to counterfactual reasoning and greater willingness to combine general explanations with detailed accounts of particular political situations. This debate was productive because it refused a simplistic division between quantitative science and interpretative geography. It asserted that the value of a method depends on the question posed, the evidence available and the standard against which an explanation is judged.

The article Tragedy of Small Power Politics, published in Geografie in 2016, showed how geopolitical theory could be used to construct explicit scenarios for a small Central European state. Kofroň investigated the strategic implications of hypothetical changes in the European security environment, rather than presenting a forecast as an inevitable future. The study drew attention to how assumptions about great-power behaviour affect conclusions about the security choices of countries such as Czechia. Its principal achievement was methodological: scenarios were made traceable to a stated theory, permitting readers to challenge either the assumptions or the deductions. The approach helped distinguish geopolitical analysis from rhetorical prediction. It also illustrated why the temporal perspective matters; security arrangements that appear stable at one moment may depend on external commitments whose future is uncertain. A discipline interested in political territory must be able to study such dependencies without claiming certainty beyond the evidence.

The work of Martin Riegl and Bohumil Doboš expanded the range of Czech scholarship on political territoriality. Riegl's writing on transformations of the political map, secession and international recognition examined why the formal status of a territory might diverge from the power exercised within it. Together, the two researchers developed comparative approaches to unrecognised entities and to relationships between recognition, political capacity and external sponsorship. Their edited volume Unrecognized States and Secession in the 21st Century, published by Springer in 2017, brought together theoretical arguments and empirical studies of contested statehood. Later work on partially independent territories challenged the adequacy of categories that divided the world into fully sovereign states and dependent possessions. The research was important for geographical classification because it showed that the global political map is less uniform than its familiar cartographic conventions suggest. Political geography could contribute by developing finer distinctions among territorial arrangements rather than treating every exception as a temporary anomaly.

Doboš subsequently extended this research towards the territorial strategies of violent non-state organisations and the geopolitical significance of new arenas. His analysis of Al-Shabaab's liquid territoriality, published in the Czech Journal of International Relations in 2020, investigated how a movement could adapt the intensity and location of its control to changing security conditions. The concept pointed to a form of political spatial organisation different from stable state administration. His books on post-Westphalian geopolitics and the geopolitics of outer space further suggested that political territory cannot always be bounded by the conventional land frontier. Whether every proposed analogy is convincing remains a

matter for scholarly evaluation; the achievement lies in formulating a comparative problem that can be debated and tested. These works also demonstrate how researchers trained in geographical thinking could enter security studies without abandoning their concern with the material and institutional organisation of space. The frontier of the subject moved from familiar European regions to places where the basic meaning of territorial authority remained contested.

The research schools were sustained by an interconnected publication system. Geografie, the journal of the Czech Geographical Society, provided a home for studies of elections, borderlands, geographical identity, military power and methodological debate. Acta Universitatis Carolinae Geographica offered another venue through which Czech and international researchers could exchange evidence and analytical approaches. Political science journals, including Mezinárodní vztahy and Acta Politologica, published work that might otherwise have remained invisible in a geographical bibliography. International outlets such as Problems of Post-Communism, Bulletin of Geography. Socio-economic Series, Europe-Asia Studies and Journal of Maps exposed Czech research to different disciplinary audiences and review standards. No single periodical can therefore be treated as the definitive archive of the subject. Recovering that history requires attention to publications that are geographical in their questions even when they appear under another subject heading.

Teaching and doctoral supervision were equally important to the accumulation of expertise. At Charles University, students could encounter political geography through a broader environment of social, regional and historical geography, while the Faculty of Social Sciences provided additional connections with political theory and international relations. At Ostrava, political and cultural geography grew through dedicated instruction linked to field studies of national and territorial conflicts. Masaryk University supported research in which political institutions, borderlands and regional development were studied in combination. The Institute of Sociology of the Czech Academy of Sciences allowed the geographical analysis of elections to develop alongside local political research and long-term social statistics. Smaller departments and other Czech universities contributed by incorporating political-geographical concepts into regional and teacher education. This institutional diversity prevented the subject from depending on the fortunes of a single department. It also required students to learn how to communicate across different evidential conventions and terminologies.

By the early 2020s, geographical information technology had changed the ordinary conditions of investigation. Detailed electoral data, historical map layers, geographical databases and spatial statistical methods allowed researchers to revisit propositions that earlier generations had tested with coarser administrative information. The study of phantom borders illustrates this change particularly clearly: a once broadly described contrast could be assessed with local indicators and mapped as an uneven spatial effect. At the same time, the increasing availability of maps did not remove the need for careful historical and social interpretation. Administrative units had changed, populations had moved and the political meanings of categories had shifted. The methodological achievement lay in combining better measurement with explicit awareness of these discontinuities. Used responsibly, digital methods strengthened the connection between questions asked in the 1990s and evidence available

three decades later. They made cumulative inquiry possible without suggesting that a longer data series could substitute for a theory of political behaviour.

The international relevance of Czech political geography was not confined to the country's experience as a post-socialist state. Its electoral research contributed evidence about democratic transition, party competition and the territorial persistence of political preferences. Its borderland studies offered cases through which theories of European integration and historical legacies could be tested. The Ostrava research programme brought empirical knowledge of disputed territories into comparative discussions of recognition, sovereignty and institutional survival. Geopolitical work associated with Prague joined debates on strategic distance, security scenarios and the limits of disciplinary separation. These contributions differed in scale and method, but all benefited from the Czech scholarly community's ability to connect precise field or documentary evidence with questions of wider theoretical interest. International engagement did not require researchers to abandon Czech cases. On the contrary, carefully investigated local histories could reveal weaknesses in generalisations developed from different parts of the world.

A critical evaluation must also recognise the constraints of the period. Research was unevenly distributed among institutions, and some themes received much more sustained attention than others. Electoral mapping accumulated richer longitudinal datasets than did qualitative studies of political participation, while research on de facto states depended on field access that could be interrupted by changing conflicts. The multiplication of English-language publications improved international reach but could make parts of the Czech-language debate less visible to external readers. Projects organised around political crises sometimes risked becoming obsolete before their conclusions appeared, while the search for internationally fashionable concepts could obscure questions of local practical importance. Czech political geographers responded to these tensions with varying success. The strongest publications were those that made their scope and limitations explicit, distinguished descriptive evidence from inference and treated rival interpretations seriously. Their intellectual contribution should not be measured only by the number of titles, citations or international partnerships recorded in an institutional report.

By 2025 the discipline had acquired a varied but recognisable body of achievements. It had reconstructed a framework for teaching political geography after the ideological restrictions of the previous era; developed long-run electoral analyses capable of linking contemporary voting to historical territorial differentiation; turned the Czech borderlands into a comparative laboratory for studying boundaries and regional memory; and created internationally visible research on non-recognised states and geopolitical territoriality. Its scholars worked in geography faculties, sociology institutes and political science departments, often bringing distinctive methods from one setting to another. The resulting intellectual landscape was plural rather than unified by a single explanatory model. This plurality was productive when disagreements led to better definitions, stronger evidence and questions that another research tradition could investigate. The record from 1993 to 2025 therefore documents more than the return of a previously constrained field. It describes the formation of a scholarly community

capable of examining how political power is organised, contested and remembered in space, and of making that inquiry intelligible within and beyond the Czech Republic.

Part Eleven

Geodesy and the Scientific Measurement of the Earth

Czech Geodesy after 1993: Scientific Traditions, Institutional Development and Technological Change

In 1993, geodesy in the newly independent Czech Republic stood at the intersection of two kinds of continuity. The country inherited a dense landscape of triangulation points, levelling benchmarks, cadastral maps and specialist institutions built over many decades. At the same time, a transformed property system, new public authorities and rapidly improving satellite measurements altered what the discipline was expected to provide. Surveyors still had to establish reliable positions on the ground, but the significance of a measured point was increasingly determined by its relationship to national digital records and European reference frames. The history of Czech geodesy from 1993 to 2025 is therefore neither a simple account of replacing optical instruments with receivers nor a story of the uninterrupted survival of an older profession. It concerns the ways in which established standards of accuracy were adapted to new legal, scientific and technological relationships. Some of the most important changes occurred within institutions whose names were familiar, while others arose through new networks and forms of cooperation.

The starting position was distinctive because Czechoslovak geodesy had combined advanced mathematical and observational work with a highly centralised system of land administration. Its survey networks had been established for different purposes and at different historical moments. The unified cadastral triangulation system, known as S-JTSK, reflected a tradition of national mapping in the first half of the twentieth century. The Baltic height system after adjustment, Bpv, supplied a corresponding practical basis for elevations. Later measurements and the needs of construction, topographic mapping and administration had added further layers of information. These inherited systems could not simply be abandoned when satellite positioning became available. Property boundaries, design drawings and state maps had been expressed in their coordinates, so any technological reform had to preserve intelligible connections to existing records. This requirement gave the Czech transition a characteristic emphasis on transformation, adjustment and verification rather than instantaneous replacement.

The political changes of 1989 and the separation of the Czech and Slovak republics in January 1993 created an immediate institutional challenge. The restitution and transfer of property rights required a system that could connect the location of land to legally recognised ownership and other rights. Under the new legislation effective from 1 January 1993, the real estate cadastre united functions previously divided among land records and systems for recording land use. Act No. 359/1992 established the framework for surveying and cadastral authorities, while the new cadastral legislation defined the records that those bodies would

administer. This was an administrative reform, but its operation depended on geodetic foundations: a parcel could not be treated as a reliable legal object without a documented relationship to maps and surveys. The practical need for an integrated record gave everyday surveying a newly visible role in the transition to a market economy. It also exposed gaps in inherited documentation, especially where the historic boundaries of privately owned land had not been fully represented in the preceding records.

For researchers and public administrators, the early cadastre demonstrated the distinction between a numerical description of land and its legal meaning. A coordinate could be precise in mathematical terms while the boundary it appeared to describe remained disputed or derived from an older map of limited positional quality. Conversely, the historical evidence for a boundary might be legally important even when its geometric representation required improvement. Czech cadastral practice consequently had to manage different kinds of uncertainty: measurement error, inconsistent map scales, missing documentation and changes in rights. These were not problems that a more accurate electronic instrument could resolve on its own. They required survey procedures, legal rules, archive research and professionally controlled updates. The experience helps explain why technological innovations in Czech geodesy were accompanied by attention to professional authorisation, official verification and the continued maintenance of original survey documents.

The Czech Office for Surveying, Mapping and Cadastre, usually identified by its Czech abbreviation ČÚZK, became the central authority through which these responsibilities were coordinated. Its functions encompassed more than the administration of individual ownership entries. It also supported the national geodetic control, official state mapping, the cadastral information infrastructure and standards for the sector. The Land Survey Office carried out work associated with geodetic foundations and state mapping, while cadastral offices and inspectorates maintained specialised responsibilities within the wider administration. The resulting division of labour established a durable relationship between national reference systems and local evidence. A surveyor producing a geometric plan for a single parcel worked within an infrastructure that also enabled engineers and researchers to connect observations over long distances. In this respect, the seemingly routine operation of a cadastral office was inseparable from national scientific measurement.

The Surveying Act, No. 200/1994, provided an additional legal basis for professional activity and defined matters to be treated as surveying in the public interest. Subsequent regulations specified reference systems, the use of state map series and procedures for authorised work. Government Regulation No. 116/1995 formally recognised a combination of national and international coordinate systems, including S-JTSK, ETRS and WGS84, alongside the established height reference. This plurality was a deliberate response to the fact that different communities required different representations of a shared territory. Cadastral practice continued to rely on a historically embedded coordinate framework, while satellite measurements acquired their meaning through global and European systems. The scientific task was to establish trustworthy relationships among them. The law did not solve the underlying geodetic problem, but it created conditions in which a solution could be implemented consistently by public bodies and private practitioners.

An early and consequential scientific inheritance was the work on European geodetic integration that had begun before the independent Czech state existed. The EUREF-CS/H-91 campaign connected selected Czechoslovak and Hungarian stations to a wider European terrestrial frame. After 1993, Czech researchers and survey authorities continued the work through the CS-BRD campaign and the DOPNUL densification of the national zero-order network. These measurements provided a bridge from a relatively sparse continental reference to stations distributed across the Czech territory. The campaigns were not an exercise in collecting new coordinates for their own sake. They allowed the distortions and local characteristics of the traditional triangulation framework to be examined against an independently realised reference. Observations therefore became evidence for assessing an older national system, not merely a more convenient way of occupying points. This combination of historical continuity and experimental comparison shaped Czech reference-frame research throughout the following decades.

Jan Kostelecký and colleagues at the Research Institute of Geodesy, Topography and Cartography played a prominent role in the campaigns and their processing. Results from DOPNUL were subsequently extended by measurements on existing triangulation and densification points. Work carried out by the Land Survey Office and cadastral authorities enabled different parts of the control network to be compared within a common framework. A 2004 account by Kostelecký and Jan Pytel documented the programme and the database of GPS observation vectors assembled to support it. The publication illustrates how the meaning of geodetic control changed in the 1990s. A national network was no longer only a set of marked places with published coordinates; it was becoming a collection of observations and adjustments that could be reprocessed when mathematical models or reference standards improved. This capacity to revisit earlier measurements was as significant as the acquisition of new field instruments.

The early densification programmes also made the consequences of heterogeneous accuracy more visible. A new satellite observation might be accurate to centimetres, yet transferring it into a traditional grid could expose irregularities inherited from older measurements and adjustments. A single simple transformation could not necessarily describe every local discrepancy. Czech geodesists therefore investigated improved realisations and correction models while recognising that an official coordinate system remained essential for routine work. The problem was particularly sensitive in a country with numerous historic cadastral maps and a long record of construction based upon S-JTSK. International comparability had to be combined with legal stability. This required a sequence of controlled changes, technical documentation and tests against independently observed points rather than an assumption that a newer system was automatically superior in every application.

The Geodetic Observatory Pecný near Ondřejov provides a second perspective on the transformation. The observatory had become part of the national research institute in 1965 and had a longer history of studying the Earth’s figure, gravity and movements. Its first GPS experiments preceded the period considered here, but regular permanent GPS observations began in September 1993. The station subsequently contributed data to the International GNSS Service from 1995 and entered the EUREF Permanent Network in 1996. These dates are

important because they show that a Czech research site became part of continuous international observation very early in the existence of the independent republic. Unlike a campaign point, a continuously operating station records changes and disturbances through time. Its scientific value derives from the continuity of the series, the stability of the monument and the documented performance of the equipment, as well as the nominal accuracy of an individual daily solution.

The Pecný observations connected Czech research to questions far wider than national mapping. Continuous GNSS data help maintain terrestrial reference frames, determine satellite orbits, investigate changes in station position and estimate the atmospheric delays affecting radio signals. The observatory's participation in international services meant that its measurements entered combinations using observations from many countries. This created a reciprocal relationship: Czech researchers gained access to common models and products, while international analysis centres benefited from a station in central Europe. The work also required a new kind of technical discipline. Receivers, antennas, clocks, software versions and monument conditions had to be recorded because changes in any of them could alter apparent movement in the time series. The observatory became a place where geodesy was practised as long-term environmental measurement rather than only as the determination of a point's fixed position.

The Research Institute of Geodesy, Topography and Cartography, known as VÚGTK, provided institutional continuity across these changes. Founded in 1954, the institute retained a combination of fundamental research and applied work in surveying, cadastre, measurement standards and spatial information. During the 1990s it operated in an environment where public agencies faced urgent demands for administrative modernisation and researchers increasingly worked through international programmes. Its former role in the International Centre for Recent Crustal Movements, active at the institute until 1996, represented one link with international geodynamic science. The continuation of the Pecný observatory and associated analysis work provided another. At the same time, research on instruments, calibration and cadastral procedures kept the institute connected to the routine needs of the surveying profession. The combination prevented the scientific and administrative branches of Czech geodesy from becoming wholly separate worlds.

The organisational status of VÚGTK changed in 2007 when it became a public research institution with ČÚZK as its founder. This step occurred within a wider restructuring of the Czech research sector and gave the institute a new formal position within publicly supported science. Its development thereafter depended on the interaction between institutional research funding, competitive grants and specialised contracts. The organisational change did not inaugurate geodetic research, which had deep roots, but it altered the conditions under which longer projects could be planned and evaluated. Laboratories and observatories need stable staff and maintenance even when a particular research question is not fashionable. The institute's continuing responsibilities in geodesy, geodynamics, metrology and cadastral methods show how Czech scientific infrastructure combined the production of publishable knowledge with services requiring continuity. Such arrangements are central to understanding why some national geodetic capabilities survived successive waves of technological change.

In parallel with the research institute, Czech universities revised the educational foundations of the discipline. The Faculty of Civil Engineering at the Czech Technical University in Prague continued to connect advanced geodesy with engineering practice, cartography, cadastre and the mathematics of measurement. The Brno University of Technology sustained its own geodetic teaching tradition, including work on engineering applications and measurement methods. At the University of West Bohemia in Plzeň, a specialised geomatics department was established in 1995, creating a distinctive institutional setting for the integration of surveying, computing, photogrammetry and geographic information. These were not interchangeable educational models. Prague linked geodesy to a broad technical university and the research activity of the capital; Brno maintained strong civil engineering connections; Plzeň foregrounded computational and interdisciplinary approaches. Together they enlarged the routes by which young specialists could enter scientific research, public administration or commercial surveying.

The spread of electronic distance measurement and robotic total stations further changed the organisation of fieldwork during the 1990s and 2000s. Angular observations, distance measurements and their initial processing could increasingly be handled within the same instrument and transferred directly to office software. For the practitioner, this reduced transcription errors and allowed the geometry of a job to be checked while still on site. For the researcher, it raised new questions concerning calibration, systematic errors and the behaviour of integrated measuring systems. Accuracy claims had to be tested under practical conditions rather than inferred solely from manufacturers' specifications. Czech metrological work consequently remained relevant even as older optical procedures declined. Electronic instruments made surveying more productive, but they also transferred part of professional judgement from the manual reading of a scale to the design, verification and interpretation of a data-processing workflow.

The metrology and engineering geodesy departments of VÚGTK represented this less conspicuous side of technological change. Calibration facilities connected routine professional measurement to traceable standards of length and instrument performance. The Koštice length baseline and associated laboratory services supported the verification of distance-measuring equipment, while specialised research addressed deformation monitoring and the automation of observations. An example is the HYNI hydrostatic levelling system described by the institute for monitoring vertical movements at the Temelín nuclear power plant. The significance of such an installation lies not only in its nominal sensitivity. Continuous monitoring requires knowledge of sensor drift, temperature effects, data acquisition and the relation between a recorded change and the behaviour of the structure. Engineering geodesy thereby became increasingly concerned with temporal stability and early detection of movement, alongside the traditional task of setting out structures at prescribed coordinates.

The commercial profession changed at the same time. The return of private enterprise created a growing market for authorised surveyors working for property owners, designers, municipalities and infrastructure companies. Jobs varied considerably, from preparing geometric plans to monitoring industrial installations or collecting 3D data for complex

construction. New equipment became available through international manufacturers and Czech suppliers, while software connected field measurements to standardised digital outputs. Yet the expansion of choice did not remove the need for common procedures. The practical value of a private survey depended on whether another professional and the relevant public authority could understand, verify and reuse its results. Standardisation was therefore not merely a remnant of centralised administration. In a market with many independent producers, consistent reference systems and documentation became even more important than they had been when a smaller set of institutions performed most of the work.

A visible transformation occurred in the information architecture of the cadastre. Inherited paper and analogue records could not provide the accessibility demanded by rising property transactions and more complicated legal relationships. During 1994–1998, the descriptive part of cadastral information was digitised on a large scale, and systematic digitisation of its geodetic component began in 1998. From 2001, cadastral data were maintained within the Information System of the Real Estate Cadastre, ISKN. This established a common technical basis for office procedures and remote access, although the completeness and positional quality of maps continued to vary from place to place. The difference matters historically. The existence of a digital record does not prove that all the measurements on which it depends were originally digital or of uniform precision. Czech cadastral modernisation therefore involved both computerisation and the much slower improvement of the underlying spatial evidence.

Public access to cadastral information developed in stages rather than through a single technological event. The free Nahlížení do katastru nemovitostí application began offering descriptive information and information about proceedings in the first quarter of 2004. Cadastral maps and georeferenced orthophotography became available through that application in the second quarter of 2008. This chronology illustrates how legal records gradually became a spatial service that ordinary citizens could inspect. The new interface made the relationship between parcels, buildings and surrounding features easier to understand, but it did not eliminate the need for specialist interpretation when a precise legal boundary was in question. The online map was a gateway to registered data, not a substitute for the evidence and measurements underlying the cadastre. By distinguishing convenient visual access from authoritative surveying procedures, the Czech system had to negotiate a challenge shared by digital land administrations across Europe.

In 2004, the cadastral administration was also reorganised into fourteen regional cadastral offices, with many existing workplaces retained as internal units. The reform reflected changes in territorial government and in the technical management of information. Central administration of the cadastral database and the standardisation of procedures offered possibilities that isolated local information systems could not easily provide. Nevertheless, the local history of cadastral maps still mattered. Some districts relied heavily on reconstructed older material, whereas others had benefited from newer large-scale surveying or land consolidation. A unified information system therefore had to accommodate records with different origins and levels of geometric reliability. This created a continuing relationship between local professional expertise and central technical control. It would have been

misleading to measure modernisation solely by the speed of a database query while ignoring the historical quality of the spatial information returned.

The new legal framework introduced by the Cadastral Act No. 256/2013 and its implementing regulations marked another stage in this development. It took effect with the new civil-law environment in 2014 and sought to align cadastral administration with contemporary property law and electronic processes. Digital geometric plans, electronically verified documents and integrated office systems gradually became more important in professional work. Their adoption brought questions of authentication and provenance into everyday surveying. An electronic file needed to identify not only the measured geometry but also the authorised person and the procedural context in which its content was accepted. At the same time, older paper evidence remained necessary where the digital representation had inherited uncertainty. The Czech experience demonstrates that a cadastral system can become electronically sophisticated without ceasing to depend on archives, field checks and the expert interpretation of historic parcel boundaries.

The national reference network underwent a more visibly scientific transition with the creation of CZEPOS, the Czech network of permanent GNSS stations for positioning. Preparatory studies were undertaken around the beginning of the 2000s, and the Land Survey Office began establishing the network in 2004 with research support from VÚGTK. Its first stages were operating before a nationwide network had been completed. By the end of 2005, the system comprised twenty-six stations, and full regular operation with twenty-seven stations began in January 2007. This chronology represents an important change in the infrastructure of precision measurement. Users no longer had to build every job around a separate occupation of a distant control point. They could connect local observations to an organised network producing correction data and archived measurements. The network made precise satellite positioning more accessible, while simultaneously increasing dependence on the quality and continuity of shared national services.

The installation of CZEPOS stations, many at cadastral offices, gave an existing administrative network a new scientific and technical role. Roof-mounted antennas observed satellite signals continuously, while communication and processing systems distributed data for post-processing and real-time positioning. The arrangement was economical partly because it relied on public buildings and institutional responsibilities already distributed across the state. Yet a receiver on a roof is not automatically a stable geodetic reference. Antenna mounting, calibration, multipath, maintenance and data communications had to be considered, as did the consistency of stations across the network. The subsequent monitoring of service performance addressed these issues by converting user experience into a form of ongoing technical evaluation. CZEPOS thus exemplified the convergence of public service and research: the same observations could help a local surveyor determine coordinates and allow specialists to investigate the reliability of the national reference frame.

CZEPOS also shows why the adoption of satellite systems should not be understood as an uncomplicated technological revolution. Real-time positioning depends on communication with a functioning network and on models that account for the relevant observational errors. A precise numerical result is useful only if the operator understands the reference frame, the

quality of the correction service and the conditions under which measurements were made. Buildings, vegetation and atmospheric disturbances affect satellite observations in ways that vary across sites and times. Czech research and professional guidance therefore continued to stress control measurements, independent checks and suitable field procedures. The state network reduced some older logistical burdens, but it created new questions of data integrity and service resilience. Its establishment changed the economics of surveying while making specialist knowledge about observation quality more, rather than less, necessary.

International connection was integral to the CZEPOS concept. Neighbouring countries were also developing permanent GNSS networks, and their stations could contribute to stronger network geometry in Czech border districts. Several Czech stations were subsequently incorporated into the EUREF Permanent Network, linking national observations to wider European reference-frame maintenance. Such cooperation mattered because physical processes do not stop at state borders, while satellite signals are received in a common global geometry. A national service designed in isolation would face avoidable inconsistencies in coordinate realisation and less robust monitoring at its edges. The Czech network developed within a regional community of operators exchanging observations and experience. Its cross-border relationships provide an instructive example of European scientific integration taking the practical form of technical compatibility and routine data exchange rather than a single highly publicised research project.

A further milestone came from the EUREF-Czech-2009 campaign and the revised Czech realisation of ETRS89 introduced on 2 January 2011. Work carried out by VÚGTK, the Land Survey Office and the Faculty of Civil Engineering of the Czech Technical University reassessed observations made across several earlier years. It connected the long-term series from permanent GNSS stations with measurements on DOPNUL and other control points and linked the solution to the European ETRF2000 frame. The achievement was methodological as well as administrative. Rather than treating the coordinates produced in the 1990s as immutable, the researchers used a more mature set of observations and international standards to construct a coherent updated realisation. Earlier measurements were preserved and reinterpreted instead of discarded. This approach emphasised the reproducibility of national geodetic foundations and made Czech practice more consistent with changes in European reference-frame science.

The repeated adjustment of old and new measurements exposed the central importance of data stewardship. Observation vectors, their covariance information, station descriptions and instrument histories must remain accessible if later researchers are to compare solutions fairly. Records stored as isolated results cannot easily be subjected to a new model or a revised coordinate frame. Czech work with geodetic databases, including projects described by Kostelecký and Pytel, recognised this need early. Over time, the same logic extended from control networks to permanent station archives and software processing centres. It also affected training: a geodesist increasingly had to judge whether an apparently precise output had a traceable observational history. The maintenance of archives and metadata was consequently a scientific achievement in its own right, although it attracted less public attention than the installation of new receivers or the launch of an online service.

At Pecný, the development of computational geodesy added another dimension. The observatory became involved in precise GNSS analysis, satellite orbit products, station coordinate estimation and methods for interpreting tropospheric delays. Its contribution to international services depended on software and processing systems capable of meeting shared standards and delivering results at demanding intervals. The research moved from campaign solutions towards near-real-time and real-time analysis while maintaining interest in long geodetic series. Jan Douša and colleagues developed methods and software for monitoring GNSS observations and processing the growing variety of satellite signals. The G-Nut library, initiated in 2011, and the Anubis quality-monitoring tool released publicly from 2013 illustrate a transition from using external software alone to producing research tools that other centres could evaluate and adopt. Such software required an understanding of both mathematical models and practical imperfections in observation files.

The emergence of additional satellite constellations made this scientific software work increasingly relevant. GPS was no longer the only usable source of navigation signals; GLONASS, Galileo and BeiDou enlarged the range of available observations, but also increased the complexity of quality control. Different frequencies, observation types, receiver configurations and data formats required careful treatment if their results were to be compared. The contribution of tools such as Anubis lay in making anomalies and missing information visible before observations entered a final adjustment. Quality assurance could therefore become a documented stage of research rather than an informal judgement reached only after an unexpected result. Czech developments in this field illustrate a wider shift in geodesy: the bottleneck was no longer always obtaining enough observations, but making an expanding volume of observations reliable, interpretable and reproducible.

Czech work on the physical foundations of measurement developed alongside the satellite positioning programmes. The observatory at Pecný combined GNSS observation with research in gravity, geodynamics and the interpretation of changes in the Earth's figure. The institute's department also participated in international activities related to terrestrial gravity, tides, DORIS analysis and satellite altimetry. These fields share questions about reference surfaces, temporal variation and the separation of different geophysical causes of an observed signal. A height measured by a levelling instrument, e.g., is not interchangeable without interpretation with an ellipsoidal height derived from satellite positioning. Establishing the connection requires knowledge of the gravity field and of the chosen vertical datum. In the Czech setting, where the inherited Bpv system remained widely used, research into physical geodesy served a practical need while contributing to the wider scientific study of the Earth. The following specialised sections will examine these techniques in detail; their historical significance here is that they kept the country's measurement infrastructure linked to fundamental geophysical science.

The change from occasional occupation to repeated and permanent observation also altered the definition of stability. In a classical survey, a monument was normally assumed to remain fixed unless a later inspection found evidence of disturbance. Continuous station records show that positions vary through a combination of geological movement, local deformation, equipment changes and observational effects. The problem is not simply to calculate a trend

but to determine which part of the apparent change has a physical meaning. Research at Pecný addressed the relation between station stability and precise reference-frame work, while engineering surveys faced analogous questions at a smaller spatial scale. The connection is scientifically important: a movement reported by a local instrument becomes convincing only when the stability of its reference is understood. Czech geodesy increasingly treated a coordinate as a value associated with a frame, an epoch and an uncertainty, not merely as a timeless pair or triple of numbers.

Another substantial part of the transformation took place in national topographic data. The Fundamental Base of Geographic Data, ZABAGED, began to be constructed in 1995 through vectorisation of the existing 1:10,000 map materials. Basic digitisation was largely completed by 2001, and the database reached its initial nationwide content in 2004. Subsequent updating made it a continuing rather than a one-time product. The historical meaning of this development extends beyond the production of digital maps. A national topographic database requires geometrically compatible features, stable identifiers and consistent definitions so that information from different places can be combined. Surveying and cartographic knowledge were therefore reorganised around the maintenance of a common geographic model. For geodesists, this increased the importance of reliable positional foundations and of the relationship between field observation, image interpretation and authoritative spatial data. The detailed evolution of ZABAGED belongs to cartography and geoinformatics as well, but its creation depended upon the same geodetic modernization described in this chapter.

Digital elevation modelling provided a particularly visible example of technological convergence. From 2009 to 2013, airborne laser scanning covered the Czech Republic and supplied the observational basis for a new generation of nationwide terrain and surface models, developed through the middle of the following decade. The programme involved cooperation among surveying authorities and other state bodies, including defence and agricultural institutions. The distinction between a bare-earth terrain model and a surface model representing buildings or vegetation was essential to its application. A large collection of laser returns could not simply be declared a map of the terrain; points had to be classified, checked and organised into a representation suitable for particular purposes. The work required flight planning, georeferencing, sensor calibration, ground control and assessment of errors. It illustrated a period in which the physical act of observing the land and the computational construction of its surface became increasingly inseparable.

The resulting digital relief models found uses in hydrology, planning, archaeology, infrastructure design and the assessment of natural hazards. The common data foundation made comparisons possible across districts that had previously relied on different surveys or topographic materials. Yet the models also revealed the limits of treating greater density as equivalent to greater truth. Vegetation, buildings, steep slopes and complicated man-made structures affected what a laser sensor could observe and what filtering algorithms might classify as terrain. A model intended for broad analysis could be unsuitable for the precise setting out of a structure without supplementary measurement. Czech geodetic organisations therefore had to define products by their geometry, intended applications and documented accuracy rather than by the novelty of the sensor alone. The laser-scanning programme helped

move geodesy towards 3D national data while preserving the need to distinguish the levels of reliability appropriate to different professional tasks.

The creation of the Basic Register of Territorial Identification, Addresses and Real Estate, RÚIAN, represented another institutional connection between surveying and the wider state information system. Established as part of the system of basic public registers launched in 2012, it brought together identifiers and location information for territorial units, parcels, buildings and addresses. ČÚZK was responsible for implementing the register, but its value depended on data maintained by several kinds of public authority. In practical terms, the register reduced the need for each office to construct its own independent description of the same territorial object. A building or parcel could be connected to other administrative records through a common identifier, while its location remained anchored in maintained spatial information. This development changed the role of the cadastre from an isolated source of property data towards a core element in the country's digital public infrastructure. It also made the quality of geodetic and address information relevant to applications far beyond professional surveying.

European cooperation supplied an important framework for the expansion of such shared information. The Czech Republic's accession to the European Union in 2004 increased the significance of interoperable spatial information, common technical standards and cross-border data exchange. Directive 2007/2/EC, establishing INSPIRE, subsequently encouraged national authorities to make environmental spatial datasets discoverable and usable through defined services and metadata. These developments did not create Czech digital cartography from nothing. They entered a field where the cadastral system, geodetic reference networks and ZABAGED were already developing. Their influence lay in strengthening expectations that publicly maintained geographic data could be combined with information from other countries and institutions. For geodesy, European standards renewed attention to coordinate reference systems, documentation, transformation procedures and the reproducibility of measurements. They also supported a shift in which public value was increasingly associated with accessibility as well as the accuracy of an individual dataset.

An additional change was the growing interaction between surveying and information technology through openly documented computational methods. At the Czech Technical University, Aleš Čepek's work on the GNU Gama adjustment software gave surveyors and researchers a freely inspectable approach to processing geodetic networks. Related educational and research activities emphasised the possibility of examining a numerical procedure rather than accepting the output of a proprietary package as an unexplained result. Such work complemented the evolution of GNSS processing at Pecný and the wider computational orientation of university geomatics programmes. Reproducibility became more demanding as data models and calculations grew more complex, but it also became more achievable when source code, algorithmic assumptions and machine-readable observations could be shared. The significance of this software culture was not that open tools displaced all commercial instruments. It was that the Czech discipline contributed to international exchanges about how geodetic results should be calculated, tested and preserved.

Professional communication provided continuity through the same period. The journal Geodetický a kartografický obzor, published jointly by Czech and Slovak surveying authorities after the division of the federation, remained a forum for practical and scientific exchange. Its move to electronic-only publication in 2013 was part of a broader change in how methods, regulations and results reached practitioners. Technical conferences, university workshops and international meetings connected employees of public offices with academic researchers and private surveyors. These channels were important because a new reference-frame realisation or electronic data format becomes effective only when it is understood and used consistently by people outside the group that developed it. The Czech and Slovak professional connection also preserved an important element of the shared disciplinary past, even as the two states maintained separate land administrations and national services. Professional debate helped turn specialised research into procedures that could be taught, criticised and revised.

During the 2010s and 2020s, a further administrative and technical development was the move towards regionally maintained digital technical maps and their connection through national information services. These datasets were designed to describe selected physical infrastructure and the spatial context needed by public authorities, network operators and construction professionals. Their implementation became especially visible in the first half of the 2020s. The approach depended on reliable measurement and updating as much as on database engineering: underground utilities and new infrastructure cannot be represented adequately by copying ordinary topographic maps. At the same time, the promise of integrated technical mapping raised questions about responsibility for updates, variable quality of older records and the treatment of information about critical infrastructure. For geodesy, the initiative expanded the range of situations in which an authenticated measurement could become part of a frequently used public digital record rather than remain a drawing associated with a single completed project.

By the end of 2025, Czech geodesy had acquired a recognisably different working environment from that of 1993. Permanent GNSS observations, digitally managed cadastral information, continuously maintained topographic databases and new elevation models had become ordinary foundations of surveying and spatial administration. The 2024 annual report of ČÚZK documented the operation of increasingly integrated services and the expansion of the digital technical mapping infrastructure, while continued research at Pecný connected the country to international geodetic analysis. These achievements should not be mistaken for the completion of every task. The positional quality of historical parcels, the reliability of measurements in difficult conditions and the maintenance of costly observation networks still required attention. Nor did digital systems dissolve differences between legal, geometric and physical definitions of location. They made those distinctions more visible and more important to practitioners who worked across several kinds of spatial evidence.

A historical assessment of the period suggests three particularly durable achievements. First, the Czech system maintained continuity with inherited national coordinate and cadastral frameworks while developing credible links to European and global reference systems. Secondly, institutions converted episodic measurement programmes into services supported

by continuing observation, accessible data and repeated quality control. Thirdly, research and education broadened the identity of geodesy by incorporating computational methods, geodynamics, metrology and the management of digital spatial information without abandoning the discipline's responsibility for exact measurement. The same history also presents a warning against a purely technological account of innovation. Satellite receivers, laser scanners and digital registers mattered because institutions undertook the slower work of agreeing standards, retaining records and checking results. Between 1993 and 2025, the Czech contribution to geodesy lay substantially in making new measurements compatible with the old territory, its legal evidence and its changing scientific interpretation.

Satellite Geodesy, GNSS Networks and International Reference Systems

The independence of the Czech Republic in January 1993 coincided with a change in how the position of a point on the Earth could be observed, calculated and shared. Satellite measurements had already entered Czech geodesy, but they were not yet the ordinary basis of surveying practice. Accurate national control still depended largely on an inherited framework of monuments and coordinates, while satellite results were obtained through campaigns that required considerable planning and specialised computation. During the following three decades the relationship was reversed. Continuous receivers produced observations throughout the day, international services supplied precise orbital information, and a surveyor could obtain a position tied to a European reference frame without occupying a sequence of neighbouring triangulation points. The Czech contribution to this transformation was not simply the adoption of equipment. It involved establishing the national connection to European geodetic infrastructure, operating scientific reference stations, developing analysis methods and building a public positioning service that gave independently acquired observations a common spatial meaning.

The intellectual foundation of this work preceded the formation of the Czech state. Czechoslovak geodesists had investigated satellite observations, terrestrial reference systems and mathematical adjustment when the practical applications of the Global Positioning System were still relatively restricted. A campaign organised within the European Reference Frame initiative in 1991 connected selected points in the former federation to the emerging European terrestrial framework. Only three of the six points observed in Czechoslovakia were situated in the territory of the future Czech Republic: Pecný, Přední Příčka and Kleť. These measurements were consequently both an inheritance from the federal period and a starting point for a distinct Czech national realisation. Their significance lay in establishing coordinates through an external European network rather than by extending an exclusively domestic survey. The early history of independent Czech satellite geodesy is therefore best understood as the continuation of a programme whose scientific and institutional horizon already crossed state borders.

A distinction between a reference system and its physical realisation is essential to understanding what the researchers accomplished. The International Terrestrial Reference

System defines how geocentric positions should be described, while successive international terrestrial reference frames realise that ideal through observations, station coordinates and velocities. The European Terrestrial Reference System 1989 takes a different practical approach, seeking coordinates that remain largely stable with respect to the interior of the Eurasian tectonic plate. A receiver does not measure an abstract frame directly. It observes radio signals from moving satellites, and its solution acquires a reference-frame meaning through satellite orbits, clocks, processing conventions and the stations used to constrain the adjustment. A Czech coordinate expressed in ETRS89 consequently depends on an established chain of scientific determinations, not merely on selecting a label in a software menu. Making that chain reliable became one of the principal tasks of the period.

Satellite positioning also altered the geodetic meaning of distance and height. Traditional networks propagated coordinates by measuring angles, lengths and height differences between adjacent points; GNSS instead relates receiver positions to satellites distributed across the sky. The underlying observables include code measurements and the phase of a radio carrier, the latter allowing exceptionally precise changes in range to be inferred once ambiguities and biases have been addressed. Geodetic results nevertheless remain vulnerable to atmospheric delay, imperfect satellite ephemerides, antenna behaviour, signal obstruction and errors in the local monument. Long sessions and network adjustments were indispensable when only a limited satellite constellation could be observed. The attraction of satellite techniques was not the disappearance of uncertainty but the possibility of modelling it in a globally consistent framework. Czech research developed at precisely this interface between the geometry of satellite observations and the demands of a long-established national coordinate infrastructure.

The first major post-federal undertaking was the connection and densification of the European framework. Measurements for the CS-NULRAD zero-order network in 1992 established an initial set of fundamental control points, and the CS-BRD campaign of 1993 connected this basis with the German reference network. The cross-border experiment mattered because coordinate consistency cannot be tested by national measurement alone: a network closed only within one country may conceal differences from the framework used immediately across its boundary. The researchers at the Geodetic Observatory Pecný processed the campaigns with precise satellite orbits, including products supplied through the emerging international GNSS infrastructure. Results from observations made on different days and with different connections had to be combined or compared under compatible modelling assumptions. The resulting framework enabled subsequent work to treat the Czech territory as one part of a wider geometric system while retaining identifiable national control points for practical surveying.

During 1993 and 1994 the DOPNUL campaign programme extended that connection across the country. The approximately 176-point network linked European geocentric coordinates with monuments of the Czech terrestrial triangulation system, with a typical separation of about twenty-five kilometres between occupied sites. It represented a considerable organisational achievement: field teams had to distribute receivers and schedule occupations, while analysts combined observations acquired in separate sessions and assessed whether individual points were sufficiently reliable. DOPNUL did not create a reference frame from nothing, nor did it

make the pre-existing network obsolete. Its achievement was to place a substantial selection of established Czech control points within the European system, enabling comparisons and transformations to be undertaken with observed common points. The network offered the intermediate geometry through which satellite positioning could be reconciled with the coordinate values required for mapping, infrastructure and cadastral work.

The relationship between ETRS89 and the older S-JTSK system remained a central scientific and operational problem. S-JTSK, based on a historical triangulation and a Křovák projection, had been retained because national maps, cadastral documentation and engineering records were already expressed in its coordinates. Satellite techniques supplied 3D positions referred to a modern Earth-centred framework, but a cadastral survey usually needed planar coordinates that agreed with neighbouring legal and cartographic records. A mathematical transformation could be designed for the two systems, yet its quality depended on the spatial distribution and reliability of common points and on distortions accumulated in the historical network. An apparently small change in the global frame could produce consequential differences when new measurements were incorporated into an old parcel map. Czech investigations therefore treated coordinate transformation as an empirical geodetic question, requiring residual analysis, local checks and explicitly stated accuracy limits.

In the second half of the 1990s, the Land Survey Office and associated research organisations continued to determine satellite coordinates for selected points in the trigonometric network. This was a gradual process of strengthening the link between satellite and terrestrial control, not a single national conversion. Field programmes undertaken between 1996 and 2006 increased the coverage of points with observed ETRS89 positions, while improvements in receivers and orbit information reduced some of the burdens encountered during early campaigns. A larger number of common points allowed regional discrepancies to be diagnosed with greater confidence. It also demonstrated that spatial density alone was insufficient: a group of observations concentrated along accessible roads or around one town might still provide an unsatisfactory geometry for transformation in a neighbouring valley. The findings helped determine where further measurements would contribute most effectively to nationwide consistency.

The analytical capacity developed in parallel with this fieldwork. Scientists needed to distinguish errors introduced by a satellite orbit from those produced by a receiver clock, a monument, a model of the atmosphere or a processing strategy. They also had to understand the implications of combining observations from several daily sessions whose geometry and data quality differed. International products supplied by the International GNSS Service became increasingly important because national laboratories could anchor their computations to a common set of precise orbits and terrestrial coordinates. The reliability of the solution depended on more than the numerical least-squares adjustment at its final stage. Antenna phase-centre models, satellite clock conventions, the treatment of Earth rotation and the selection of stable reference stations all entered the calculation. The repeated comparison of independent solutions became a practical expression of geodetic science: measured positions were accepted through their reproducibility within a documented model.

Pecný near Ondřejov acquired a particularly important place in this system. The Geodetic Observatory had a history of astronomical and geodetic research, but continuous satellite tracking gave it a new international role. On 7 September 1993 the GOPE station began permanent GPS observations with a geodetic receiver, replacing the intermittent character of campaigns with a nearly continuous record. The first years required experimentation with recording, transmission and routine operation; regular contributions to the international service began in 1995, and GOPE entered the European Permanent Network in 1996. The station became a reference for studies of coordinates, satellite orbits and the atmosphere as well as a practical connection between Czech measurement campaigns and foreign analysis centres. A long time series at a single monument was valuable because it could reveal changes that would remain invisible in a few isolated observation sessions.

The move to permanent observation also transformed the research problem. A campaign provides coordinates at an epoch, whereas a continuously operating receiver provides a time series that can be examined for seasonal signals, changes of equipment, interrupted observations and possible motion of the station itself. Differences between daily solutions may arise from several sources, and their interpretation depends on the record of what happened at the instrument. A replacement antenna, an altered radome or a change in the immediate surroundings can produce a discontinuity resembling ground movement. For GOPE, the maintenance of station logs and the preservation of observations were therefore part of the scientific record. The station's value came not merely from the precision of a particular day's solution, but from the accumulated evidence needed to decide whether a difference was geophysical, technical or computational.

The development of GOPE illustrates this combination of continuity and technical change. Routine reporting to overseas processing centres became possible as data transmission improved during 1995, while hourly data products began to support more rapid processing in the late 1990s. In November 1999 the original GPS receiver was replaced by an instrument able to observe GLONASS as well, together with a geodetic choke-ring antenna. This enlarged the available set of satellite observations and exposed analysts to differences between constellation designs and signal characteristics. Another major equipment change occurred in December 2009, when a newer receiver and antenna replaced the earlier system. Each change required attention to the consistency of the historical coordinate series. The scientific challenge was to benefit from improved tracking while retaining the ability to compare results across generations of instrumentation and processing conventions.

The observatory did not work in isolation. In Brno, a permanent station designated TUBO developed through cooperation between the Research Institute of Geodesy, Topography and Cartography and the Faculty of Civil Engineering at Brno University of Technology. Established in the 1990s and operating continuous GPS observations from 2001, TUBO supplied an additional Czech connection to the European network. Other university and experimental stations gradually broadened the range of observation environments, including sites in industrial cities and upland areas. These installations could fulfil different functions: some provided a stable regional reference, some supported tests of new equipment or communication methods, and others helped investigate local geodynamic or atmospheric

processes. Their coexistence encouraged exchange between official geodetic practice and university research. The national GNSS landscape was consequently plural rather than the product of one administrative network.

The EUREF Permanent Network offered Czech geodesists a scientific organisation that could extend the usefulness of national observations beyond their immediate collection sites. Its stations are not a single centrally owned array; they are contributed by agencies and universities that agree to follow compatible rules on instruments, metadata, observation formats and analysis. Individual centres process parts of the network, and their solutions are combined to form reference-frame products. Pecný became one of the European analysis centres and, from 2002, also operated a local data centre. This distinction between observing and analysing was fundamental. A Czech receiver could contribute to a coordinate solution spanning several countries, while computations made at Pecný could help determine positions far beyond Czech territory. The national research programme thus acquired an international scope through routine responsibility for a shared scientific service rather than through occasional cooperation alone.

Operating an analysis centre meant maintaining a repeatable calculation under strict time constraints. Observations had to be retrieved from many stations, checked for gaps and inconsistencies, associated with the relevant satellite orbits and antenna models, and processed into daily or weekly estimates. Those estimates were useful to the network only when they satisfied agreed standards and arrived on schedule. Much of this activity was invisible in the final coordinate catalogue, yet it created the continuity on which scientific comparisons relied. Work at Pecný involved not only geodetic theory but also automated data handling, computing infrastructure and software engineering. Researchers learned to trace an unexpected station displacement backwards through the sequence of raw observations, metadata and modelling decisions. This practice produced a more demanding conception of measurement quality: an accurate coordinate was a reproducible result of a documented processing system, not an isolated numerical output.

The International GNSS Service supplied a wider framework in which this Czech expertise could develop. The service combined observations and solutions from institutions around the world to provide precise orbit, clock and reference-frame products. For a national network, access to these products reduced reliance on broadcast satellite ephemerides, whose accuracy was designed primarily for navigation rather than high-precision geodesy. For an analysis centre, however, use of international products also brought an obligation to investigate their quality and limitations. Czech researchers examined discrepancies between alternative orbit solutions, the impact of Earth-orientation modelling and the consequences of prediction errors for rapid positioning. The scientific gains were cumulative: improvements to the global constellation solution increased the accuracy of national surveying, while observations from Czech stations strengthened the multinational geometry from which the global products were computed.

From 2004 to 2015, Geodetic Observatory Pecný served as an analysis centre of the International GNSS Service for ultra-rapid GPS and GLONASS orbit products. The task differed from determining the coordinates of fixed ground stations. It required estimation or prediction

of a satellite's position and the evaluation of how the errors in that orbit would affect subsequent users. Ultra-rapid products are especially difficult because part of the interval concerns an orbit for which observations have not yet arrived. Timely delivery matters alongside numerical precision. The Czech contribution supplied one of the independent solutions that could be compared and combined within the international service. Its later interruption for funding reasons is also instructive: sophisticated scientific operations require a dependable financial and technical base, and even a highly qualified research group cannot maintain an international production obligation indefinitely without resources for continuous service.

Satellite-orbit determination connected geodesy with celestial mechanics, time measurement and the changing orientation of the Earth. A receiver's apparent distance to a satellite depends on when the radio signal was transmitted, the satellite's clock and orbit, and the rotation of the Earth during signal travel. Earth-orientation parameters are not optional refinements when a solution aims at centimetres or millimetres. Nor is an orbit merely a sequence of positions copied from navigation messages: a precise orbit is computed using dynamical and observational information, including the effects of gravity and non-gravitational forces. The analytical programmes developed at Pecný familiarised Czech researchers with these dependencies. They also highlighted why national reference-frame work cannot be isolated from global conventions, since an error in a common orbit or clock product can enter the inferred coordinates of many otherwise independent stations.

By the beginning of the new century, atmospheric effects had become another major field of satellite-geodetic cooperation. Radio signals are delayed by their passage through the ionosphere and the neutral atmosphere. Dual-frequency observations permit the leading ionospheric effect to be removed or estimated, but the tropospheric contribution requires additional modelling and often becomes a parameter to be inferred from the data. For geodesists it is an error source affecting heights and other coordinates; for meteorologists the same delay contains information about atmospheric water vapour. Czech researchers at Pecný developed procedures for estimating zenith total delay from permanent stations and delivering results quickly enough to be useful in numerical weather prediction. The work connected satellite positioning with the COST-716, TOUGH and E-GVAP initiatives and showed how a geodetic measurement could become an environmental observation without losing its original reference-frame purpose.

The creation of CZEPOS marked a decisive change in the relationship between a national reference framework and the working surveyor. The Czech Office for Surveying, Mapping and Cadastre initiated construction of the Czech network of permanent positioning stations in 2004, using sites at cadastral offices and linking selected external receivers. The initial concept provided nationwide coverage through a relatively small number of carefully distributed stations. During 2005, an experimental service was expanded and the distribution of data and corrections began. Instead of setting a second receiver on a nearby control point for every survey, a user could obtain observations or network-derived corrections from a permanent service. The achievement was particularly important for everyday geodetic operations, where the capacity to establish consistent coordinates efficiently could have greater practical value

than a small improvement in the best accuracy obtainable through a carefully designed research campaign.

The early CZEPOS service had several layers. Archived observations enabled post-processing of field measurements against a known reference station, while real-time corrections supported positioning at the moment a receiver was used. Methods such as real-time kinematic positioning exploited carrier-phase observations and information shared between a rover and the permanent reference infrastructure. Network variants, including virtual reference station techniques and area-correction approaches, attempted to represent spatially varying errors rather than simply applying corrections from one physical base. These methods did not abolish the importance of baseline length or local measurement conditions. They reduced some correlated errors and enlarged the practical area over which high-precision results could be obtained. Their introduction called for scientific testing of solution stability, coordinate agreement and the circumstances under which an apparently precise real-time result might nevertheless be wrong.

CZEPOS also required a clear division between infrastructure operation and the evaluation of its scientific performance. Station owners had to maintain receivers, antennas, communication links and backup facilities; a central service had to archive observations, distribute products and manage user access. Geodetic researchers needed to test whether the published station coordinates remained consistent with their assigned reference frame and whether the service reproduced accepted control across different areas. Pecný's work in monitoring the national positioning service from 2006 illustrates this interaction. A permanent station is not trustworthy simply because it broadcasts continuously. Its coordinates may drift through monument instability, its receiver may develop biases, or an interruption in real-time communication may leave a field crew unaware of degraded corrections. Independent monitoring turned the network from an attractive technical system into a reference infrastructure whose performance could be questioned and documented.

The spread of permanent stations did not eliminate the need for the older DOPNUL and trigonometric monuments. Instead, the two types of control acquired complementary roles. The satellite network supplied a dynamic observational basis and convenient access to ETRS89, while the established terrestrial points represented decades of mapping and legal measurement in S-JTSK. Using them together required careful decisions about which coordinates should be treated as fixed, how distortions in historical geometry were represented, and what accuracy could be promised for a transformed result. Some field surveys were conducted primarily to verify transformations, not to increase the density of satellite observations for its own sake. The success of satellite geodesy in public administration thus depended on preserving and understanding records from an earlier technical generation. Czech practice shows that technological change in geodesy is more often a controlled reconciliation of systems than an abrupt replacement.

The national reassessment of ETRS89 brought these questions to the foreground. On 2 January 2011 a new Czech realisation came into force, adopting the ETRF2000 frame in place of the previous ETRF89 basis. The change followed a research programme undertaken with the participation of the Research Institute of Geodesy, Topography and Cartography, the Land

Survey Office and the Faculty of Civil Engineering of the Czech Technical University in Prague. Long observation series from CZEPOS and other permanent stations were combined with selected European reference stations. Historical GNSS measurements from the DOPNUL network and later survey campaigns were then introduced through successive adjustments. The procedure gave both permanent stations and terrestrial control points a common revised coordinate basis. The date of implementation is significant because it marks a documented change in the realisation of a reference system that retained its familiar name.

The 2011 revision was more than an administrative update of coordinate tables. It used the long-term behaviour of permanent stations to link national observations to the European network and involved renewed processing of measurements accumulated over many years. The resulting adjustment had to distinguish the internal geometry of the Czech measurements from the constraints imposed by the broader reference frame. This distinction matters because an overly rigid treatment of a few published coordinates can conceal inconsistencies, while a completely unconstrained solution may have no stable geographical orientation. The choice and weighting of reference stations were therefore part of the scientific result. Incorporating observations from different periods also required the analysts to account for changes in equipment and processing standards. The revised frame provided an opportunity to correct inherited discrepancies without pretending that all older field records had possessed the same accuracy.

One practical consequence was the need to reconsider transformations from ETRS89 to S-JTSK. A programme written for the older reference realisation could no longer be assumed to give compatible national map coordinates after the 2011 change. Czech authorities published guidance on approved transformation procedures, their periods of validity and the geographical limits within which stated accuracy could reasonably be expected. Conversion grids were progressively revised, including updates made available in 2012 and 2018. The history of these revisions is important because it reveals a subtle source of error in modern surveying: two competent users can observe the same point with similar GNSS equipment and still obtain different national coordinates if their software applies different transformation models. Consistency depends on versioned definitions, documented procedures and the ability to reproduce an earlier calculation.

The transformation issue also showed why reference frames must be treated as time-dependent scientific constructions. The International Terrestrial Reference Frame includes station velocities because the crust is moving, whereas ETRS89 is designed for a different kind of stability within Europe. The relationship between them depends on the epoch for which coordinates are required and on the conventions adopted for plate motion. A precise position observed in one year is not automatically identical in every later realisation, even if the physical monument has remained apparently undisturbed. Czech scientists working with European solutions therefore had to interpret coordinate changes caused by new observations separately from changes introduced through a revised reference frame. This task became more important as monitoring extended over decades. The concept of a permanent control point acquired a more sophisticated meaning: its material stability had to be tested through a record that acknowledged movement, uncertainty and changes in international standards.

The European network's repeated reprocessing campaigns addressed one major cause of inconsistency in historical data. Ordinary daily GNSS solutions may use whatever orbit products, antenna calibrations and estimation strategies were accepted when the day was originally processed. Joining them into a long series can therefore produce discontinuities arising from scientific progress rather than Earth motion. In coordinated reprocessing, observations from earlier years are analysed again under harmonised conventions. Pecný participated in the European reprocessing efforts, including the campaigns associated with 2008 and 2014. The latter involved the reanalysis of observations extending back to 1996 and tested the compatibility of independent processing packages. The result was not a return to obsolete data for historical curiosity. It made earlier measurements scientifically comparable with recent ones and improved the interpretation of station velocities and reference-frame stability.

This work demanded attention to the physical antenna as well as to the mathematical adjustment. Antenna phase centres do not coincide with a single point independent of signal frequency or satellite direction, and their calibrated variations affect the inferred receiver position. A change in the assumed antenna model can therefore alter an entire time series. Czech participation in European processing helped put such corrections into a shared methodological framework. Software comparisons were similarly revealing: when different algorithms gave divergent coordinates from identical observations, analysts needed to determine whether the source was a modelling choice, a numerical implementation or the handling of incomplete data. Reprocessing strengthened the argument that a geodetic reference frame is a collective scientific result whose accuracy depends on the quality and transparency of processing conventions. It also gave Czech researchers opportunities to evaluate global assumptions against the dense network of observations available in Central Europe.

A further extension came through experimental and geodynamic observation networks. The Research Institute of Geodesy, Topography and Cartography operated the VESOG experimental environment alongside the long-established station at Pecný and partnerships with universities. The Institute of Rock Structure and Mechanics of the Czech Academy of Sciences developed GNSS observations associated with GEONAS and geodynamic research in regions where geological structures or historical seismic activity invited long-term monitoring. These networks differed from CZEPOS in purpose and ownership. Some stations contributed primarily to the integrity of a national positioning service; others were selected to examine movement or to test technical procedures. Their data could nevertheless strengthen regional reference-frame solutions and improve the interpretation of local changes. Treating them as complementary rather than interchangeable preserved the distinction between a stable control service and a scientific experiment designed to observe possible instability.

The transition from GPS to multi-constellation GNSS changed both observation geometry and research methods. GLONASS measurements had been incorporated at Pecný by 1999, but the later development of Galileo and BeiDou introduced a more substantial enlargement of the observable system. Receivers increasingly tracked several frequency bands, signal modulations and orbital constellations. The advantage was not simply a larger satellite count.

Additional observations could improve the likelihood of obtaining useful geometry in difficult environments and create new combinations for handling ionospheric delays and ambiguity resolution. They also increased the number of hardware biases, inter-system offsets and signal-specific decisions that analysis software had to accommodate. Czech GNSS specialists therefore faced a new version of an old problem: more information improved positioning only when its differences were understood. A multi-system solution could be less trustworthy than a carefully controlled GPS-only analysis if incompatible measurements were combined without adequate modelling.

The development of the G-Nut software family at Pecný was an important response to this methodological change. Initiated in 2011, the library was designed to support a variety of GNSS data analyses within a common software architecture. Pavel Václavovic, Jan Douša and Gabriel Györi described the project in a 2013 publication that explained how processing components could serve positioning, time-series evaluation and atmospheric estimation. The choice of a modular architecture was significant because GNSS constellations and observation formats were evolving too quickly for a single-purpose programme to remain adequate without continuing revision. Some tools built on the library were released for wider use, giving researchers outside the observatory access to procedures developed through Czech experience. The project represented a shift from the operation of specialised local algorithms towards maintaining adaptable software as a research output in its own right.

The Anubis application developed within G-Nut addressed the quality of multi-GNSS observations before they entered a final coordinate solution. Its analysis could identify issues such as missing epochs, interruptions, unusual signal behaviour and cycle slips in carrier-phase measurements. These are not minor housekeeping details. A coordinate estimate based on extensive but unreliable observations can carry a deceptively small formal uncertainty, while a well-documented exclusion of poor data may produce a more defensible scientific result. Václavovic and Douša's 2016 publication presented Anubis as an open-source approach to multi-GNSS monitoring. The significance of the work lay in making data quality itself a subject of repeatable examination. It also helped operators compare stations whose equipment and tracking capabilities differed, an increasingly necessary task as national and international networks combined multiple receiver generations.

Other G-Nut applications extended the analysis towards precise point positioning, atmospheric products and coordinate time series. Software such as Tefnut used satellite observations and precise orbit and clock information to estimate tropospheric delays, while related tools examined station coordinates or model parameters generated by numerical weather prediction. A 2014 study by Douša and Václavovic demonstrated real-time zenith delay estimation intended to support atmospheric forecasting. In 2018, Douša, Václavovic, Lewen Zhao and Michal Kačmařík published a more adaptable strategy combining real-time and near-real-time approaches. These developments illustrate the importance of precision products for independent processing at a receiver: network differencing is not the only possible path to an accurate estimate, but alternative strategies require careful modelling of errors that differencing would otherwise help reduce. For Czech geodesy, this line of research deepened international participation while giving domestic researchers reusable analytical tools.

The growth of multi-GNSS observations reached the national positioning service through successive technical upgrades rather than a single changeover. CZEPOS expanded its ability to distribute corrections based on GPS, GLONASS, Galileo and BeiDou, and in October 2019 introduced a renewed network solution incorporating all four systems. A further single-station real-time service followed in September 2020. In August 2021 a new application for post-processed data provided observations in RINEX 3, replacing an older interface built around RINEX 2 files. These details matter historically because they indicate that the national infrastructure moved beyond the first generation of GPS corrections towards a service able to use diverse satellite signals and modern data definitions. They also show how a technical innovation became operational only after the receiver network, communication links, formats and user software were made compatible.

The interaction between GNSS and the atmosphere became increasingly sophisticated during the 2010s. Real-time observations opened the possibility of generating rapid estimates of atmospheric delay for comparison with meteorological analyses. Yet the scientific problem was not solved simply by shortening data latency. Receiver noise, uncertainty in satellite products, severe weather and incomplete tracking could all influence the resulting series. Czech work addressed these limitations through improved estimation strategies, independent validation and database systems for comparing atmospheric products. Participation in the GNSS4SWEC cooperation connected the Pecný team with a European community investigating severe-weather and climate applications. It also encouraged a closer examination of what could genuinely be inferred from satellite signals. Zenith delay is an observed geodetic parameter; interpreting it as atmospheric water vapour requires further thermodynamic assumptions and external meteorological information.

Cross-border compatibility remained a practical test of the European reference programme throughout the period. A railway survey, regional map or infrastructure project may extend from Czechia into Germany, Poland, Austria or Slovakia, where the immediate positioning services and historical national projections differ. The relevant question is not whether two receivers display coordinates under the heading ETRS89, but whether their solutions use compatible realisations, epochs and transformation procedures. International reference stations and shared technical standards reduce discrepancies, while domestic guidance defines how results must enter the Czech cadastral and mapping systems. This made EUREF cooperation valuable for much more than academic comparison. It helped establish the conditions for data generated by different agencies to refer to a common geographical reality, even when each country retained legal requirements and historical maps expressed in its own national coordinate system.

The wider deployment of GNSS also raised questions about continuity of access, operational responsibility and user expectations. Internet links and power supplies became parts of the geodetic instrument in a functional sense, because a real-time service could not provide useful corrections without them. Users of automatic construction machinery, surveying equipment or agricultural guidance systems might depend on a continuous data stream whose reliability was controlled elsewhere. This did not mean that the research institute could guarantee every private application. It meant that the accuracy of national positioning increasingly depended

on the governance of a shared service, on independent checks and on clear explanations of degraded conditions. The case of CZEPOS suggests a broader lesson about scientific infrastructure: a reference network becomes socially significant when the results of complex scientific work can be supplied consistently to many users who do not themselves participate in the original analysis.

Developments during the 2020s made the distinction between precision and reliability particularly visible. Strong ionospheric activity can degrade GNSS positioning even when many satellites are available, while the introduction of new frequencies and constellations requires continuing verification of network models. In February 2025 the CZEPOS operator reported an upgrade that supported further signals, including BeiDou-3 and Galileo E6, and enhanced a service for visualising residual ionospheric and tropospheric errors. The explanation linked the change to an expected maximum in the solar activity cycle. This was a useful example of an operational improvement directly informed by geophysical considerations. More signals expanded the capacity of the system, but users still needed information about the changing conditions under which centimetre-level results could be sustained. The upgrade shows why modern reference networks must continue to evolve after their initial construction.

Scientific education formed an important, if less visible, part of this development. The Czech Technical University in Prague and Brno University of Technology maintained training in adjustment theory, advanced geodesy and the interpretation of reference systems, while specialists at Pecný contributed research expertise and examples from the operation of permanent networks. Students could progress from conventional survey control to the dynamics of satellite orbits and the statistical treatment of time series without treating these as unrelated branches of measurement. The increasingly accessible GNSS service offered practical experience, but rigorous teaching also had to explain its limitations. A coordinate supplied almost instantaneously is not self-validating, and the formal accuracy displayed by field software does not replace independent control. Training a new generation of geodesists therefore required a combination of computational understanding, knowledge of national systems and disciplined field practice.

By 2025 the Czech system had acquired an architecture quite different from the network of intermittent campaigns that existed at independence. GOPE and other long-running scientific stations contributed to international services; CZEPOS provided domestic access to a maintained national reference; and research groups developed processing, monitoring and transformation methods that helped connect these levels. This architecture had no single centre of expertise. The Land Survey Office carried operational responsibility for national positioning, the Research Institute of Geodesy, Topography and Cartography contributed scientific analysis, and university and Academy teams supplied further research and observations. Its strength lay in the possibility of checking the same geographical quantity through different institutions and methods. The interaction also exposed limits: maintaining quality depended on funding, transparent metadata and sustained cooperation, not solely on the next generation of satellite hardware.

The period from 1993 to 2025 can consequently be understood as a transition from establishing a national satellite-geodetic connection to maintaining a continuously observable and

internationally compatible terrestrial reference frame. Early Czech campaigns established common points through which ETRS89 could be related to older coordinates. Permanent observations then made it possible to examine the stability of these connections through time, while the growth of CZEPOS brought the framework into routine practice. International analysis, homogeneous reprocessing, multi-GNSS software and the 2011 ETRS89 revision demonstrated that precision must be maintained through scientific evaluation rather than assumed from the age of an instrument. The lasting achievement was the creation of a research and service environment in which a coordinate could be measured, verified, transformed and interpreted with explicit knowledge of its reference frame and observational history. That foundation supported applications far beyond geodesy itself, while leaving specialist questions of gravity, deformation and atmospheric interaction for further investigation.

Physical Geodesy, Gravimetry and the Study of Earth Dynamics

The development of physical geodesy in the Czech Republic after 1993 can be followed through a deceptively simple question: what does the height of a place actually mean? A position fixed by a satellite receiver is expressed with respect to a mathematical ellipsoid, whereas a surveyor establishing an elevation, an engineer designing a watercourse and a scientist examining a moving crust require knowledge of the Earth's gravity field. During the period from independence to 2025, Czech geodesists brought these forms of measurement into increasingly close agreement. They refined national height references, investigated variations in gravity, made use of satellite observations and studied movements that could alter the interpretation of a stable benchmark. These tasks were connected by the physical character of the Earth rather than by a single instrument. A reference surface, a gravity station and a repeated levelling route all provided different evidence about one changing planet.

Physical geodesy differs from the geometrical determination of coordinates because it studies the potential of the combined gravitational and centrifugal forces that govern the direction of the plumb line and the behaviour of level surfaces. A gravimeter measures acceleration at a particular place and time, not an immutable property of the ground beneath it. An absolute instrument establishes a value with reference to physical units; a relative instrument determines a difference between stations; a continuous instrument reveals variations that might be missed by occasional observations. Geodesists must distinguish the effects of altitude, topography, atmospheric pressure, tides and redistributed water from changes associated with deeper Earth processes. This interpretation relies upon physical modelling and carefully estimated uncertainty. The methodological achievement of Czech research was therefore not merely to collect more precise values but to connect measurements made for very different purposes into a coherent account of gravity, height and motion.

The independent Czech state inherited an unusually extensive infrastructure for such work. Former Czechoslovak programmes had established national levelling and gravimetric networks, undertaken gravity mapping for geological exploration and trained mathematicians concerned with the geoid and Earth rotation. The Research Institute of Geodesy, Topography

and Cartography, together with technical universities, geophysical institutes and observatories, maintained a tradition that was both theoretical and experimental. Geodetic Observatory Pecný, situated near Ondřejov, provided a particularly valuable meeting point between stationary instruments and nationwide measurements. Earlier knowledge did not disappear when the Czech and Slovak administrative systems separated. Instead, existing reference points, maps and observation series became the material from which the new republic developed its own nationally maintained networks and participated in European comparisons. The history of the period begins with this conversion of inherited scientific capacity into a modern infrastructure capable of being independently checked.

For a country bounded by the Bohemian Massif and neighbouring Central European regions, the relations between geology, topography and gravity were never peripheral concerns. The crystalline rocks of the massif, the basins of north-western Bohemia, the mountainous frontier and the varied structures of Moravia create substantial spatial differences in measured acceleration. The national height system, known as the Baltic Vertical Datum after adjustment, or Bpv, also rests on a historical framework of precise levelling and normal heights. Transforming observations made in that framework into ellipsoidal heights involves much more than selecting a constant offset. The separation varies geographically and must be represented by a quasigeoid, derived from gravity information and evaluated against independent height observations. In the 1990s this requirement gave Czech physical geodesy both a practical problem of national importance and a demanding test of its mathematical methods.

The first decade after independence was marked by the growing ability to compare classical ground surveys with satellite-derived positions. Repeated GPS campaigns allowed researchers to observe the same stations in a geocentric framework, while high-precision levelling retained its role in establishing differences of physical height. Gravity surveys supplied the missing connection between these descriptions. A discrepancy between an ellipsoidal height and a levelling-derived height could reflect errors in measurement, inadequacies in the quasigeoid model, movement of the station or incompatible definitions of the reference frame. Consequently, a useful comparison required systematic attention to the observing epoch, the quality of the monument, the adjustment of the vertical network and the assumptions of the gravity calculation. Such questions pushed Czech researchers towards the integration of several independent observational systems rather than reliance upon one apparently superior technique.

The institutional setting was deliberately broader than a single surveying organisation. The national surveying authority and its Land Survey Office were responsible for the geodetic foundations on which public mapping and engineering could rely. The Research Institute of Geodesy, Topography and Cartography investigated methods and instruments, while the Czech Technical University in Prague educated specialists in surveying and mathematical geodesy. The Geophysical Institute and the Institute of Rock Structure and Mechanics of the Academy of Sciences addressed seismic activity, fault displacement and Earth dynamics. Research teams at technical universities in Brno and Ostrava contributed to applied and regional geodetic studies. Their work overlapped without becoming identical. Legal responsibility for maintaining reference points was not the same as scientific responsibility for

testing a geophysical hypothesis, and distinguishing these tasks helped explain why collaboration among the institutions became increasingly important after 1993.

Gravimetry was one of the clearest examples of continuity through technological change. The Czech lands possessed extensive older records of gravity anomalies, originally assembled in part for geological prospecting and regional mapping. Their geographical coverage made them valuable for determining the fine structure of a national gravity field, but the observations had been acquired with different instruments, coordinate systems and methods of height determination. By the 1990s, digitisation made it possible to recover these records for new calculations. The challenge was to distinguish legitimate physical contrasts from inconsistencies caused by the recording process. A value measured decades earlier did not become worthless merely because its instrument was less precise. It could still constrain a regional model, provided that its origin, reduction and uncertainty were understood. Modern physical geodesy thus relied upon critical reuse of historical data as much as upon newly installed equipment.

Gravity reference stations supplied the stable numerical basis for combining observations made across the territory. Absolute gravimetry determines acceleration through the motion of a freely falling test mass and allows measurements to be compared with those from other countries without dependence on a long chain of relative differences. Relative measurements remain essential for densifying networks and identifying small spatial contrasts at a manageable cost. The two forms of observation are most useful together: an absolute station anchors a survey, while relative gravimeters transfer values between sites and reveal their local relationships. In practice, the stability of the station and the calibration of the instrument matter as much as the nominal resolution displayed by the device. The Czech programme increasingly addressed these requirements through repeated observations, instrumentation tests and participation in international comparisons.

A major change occurred at Pecný in August 2001, when the FG5-215 absolute gravimeter entered service. The instrument enabled repeated determinations of gravity at the observatory and at other stations of the Czech network, and its use was extended to measurements in Slovakia and Hungary. A common observational instrument did not automatically make all surveys comparable, because differences in atmospheric conditions, instrument setup, vertical gradients and local water storage could affect the result. Nevertheless, the possibility of returning to a reference station with a high-precision absolute gravimeter made temporal variation a practical research question. In addition to supporting the modernisation of gravity networks, the observations allowed researchers to ask whether a measured difference across several years represented a physical change, an instrumental offset or some combination of the two.

At the beginning of the century, regular measurements of Earth tides at Pecný still employed instruments based on mechanical springs. Those records made an important contribution to the analysis of the periodic gravitational effects of the Moon and Sun. Their limitations, however, became apparent when geodesists wished to investigate slower changes in environmental loading or signals associated with geodynamic processes. The installation of the superconducting gravimeter OSG-050 in February 2007 greatly expanded the observational

range. By maintaining a test mass in a superconducting magnetic field, the instrument could record minute changes in acceleration continuously with long-term sensitivity that complemented the intermittent absolute measurements. It thereby transformed a station that established gravity at selected moments into a site capable of observing the temporal structure of the gravity signal itself.

The combination of the absolute and superconducting instruments at Pecný was methodologically significant. An absolute gravimeter could constrain the level and calibration of the superconducting record, whereas the continuous record could reveal changes that occurred between two absolute occupations. Neither instrument was wholly self-sufficient. The superconducting gravimeter exhibited characteristics of its own response and drift, and the absolute observations required environmental corrections and an assessment of systematic uncertainty. Their joint interpretation led to improved gravity reference functions and tests of whether measurements taken years apart could be compared without artificial discontinuities. This was a distinct achievement of Czech gravimetric research: precision was understood as a property of an entire measurement chain, extending from the physical reference to the treatment of temporal effects, rather than as an isolated specification of an expensive instrument.

The tide signal itself supplied a bridge from local observation to global Earth dynamics. Periodic deformation of the solid Earth and the attraction of oceanic water change gravity even at an inland station. Atmospheric and hydrological loading introduce additional movements and gravitational effects, some of which occur over comparable periods. In interpreting a continuous record, researchers must therefore model predictable tidal contributions and then examine the residual variations rather than treating every unusual fluctuation as a tectonic event. The long Pecný series offered opportunities to study long-period tides, signals accompanying major seismic disturbances and the environmental conditions responsible for smaller changes. By combining astronomical prediction, gravimetric observation and local meteorological information, Czech geodesists placed the observatory within international investigations of how the Earth responds to forces that operate across many temporal scales.

Environmental gravity correction became a research subject in its own right. At Pecný, an increase in soil moisture could modify acceleration through the added attraction of water close to the instrument, while changes in groundwater and broader continental storage could create signals of different magnitudes and phases. A simple correction based on rainfall totals was insufficient, because identical precipitation could produce different subsurface distributions depending on antecedent conditions, topography and drainage. Investigators used information on local water levels, soil moisture and terrain to calculate the attraction of variable water masses around the observatory. The resulting models revealed why hydrological effects cannot automatically be regarded as noise. They are measurable physical processes whose influence must be separated from tectonic signals, and their analysis provides a connection between precise geodesy and research on the water cycle.

The 2010 study by Vojtěch Pálinkáš, Jakub Kostelecký and Jaroslav Šimek made these methodological challenges unusually explicit. Using experience with the FG5-215 gravimeter, the authors examined instrumental reproducibility alongside atmospheric and hydrological

influences on repeated absolute gravity observations. Their discussion treated the possibility of detecting geodynamic change as a question of demonstrated measurement capability, not simply one of increasing decimal precision. The study also illustrated the use of a local topographic model to estimate the gravity attraction of variable water stored within the ground around Pecný. This approach required the observatory to be understood as a physical environment with a specific relief and hydrology. It drew attention to a general limitation of gravity monitoring: a well-resolved variation is not necessarily a well-explained one, especially where several mass-redistribution processes may act simultaneously.

The implications were tested over a wider area in the investigation by Pálinkáš and colleagues published in the Journal of Geodesy in 2013. The researchers examined repeated absolute observations from 1991 to 2010 at sites in the Czech Republic, Slovakia and Hungary, considering both instrument-related and hydrological effects. Some stations appeared to show declining gravity, but the interpretation changed when systematic differences between instruments and possible water-storage variations were assessed. The scientific importance of the paper lay in resisting a direct equation between measured gravity decrease and regional tectonic uplift. A repeated measurement can indicate a real change in the observed field while leaving its causes unresolved. By subjecting the data to cross-instrument comparison, the authors converted a potentially dramatic geodynamic claim into a careful analysis of what the evidence could legitimately establish.

An international comparison of gravimeters is more than a competition over the smallest reported uncertainty. It exposes differences in scale, instrumental offsets, alignment, measurement practice and correction procedures. For a national reference laboratory, participation also establishes whether local observations are compatible with measurements made under equivalent conditions elsewhere. The Pecný team participated in successive international comparisons of absolute gravimeters and developed procedures for reporting gravity values with traceable uncertainty. By the 2020s, this metrological programme had become closely connected to the International Terrestrial Gravity Reference System. The purpose was to create gravity values that could be reproduced and independently checked, even when the instrument, operator or observing date changed. Such comparability is essential for interpreting slow geodynamic processes whose expected signals may be smaller than the systematic errors of an uncalibrated measurement series.

The Czech programme expanded its repeated measurements of absolute gravity during the period after 2020, paying particular attention to seasonal variations at reference stations. Work reported by Pálinkáš, Kostelecký and Miloš Vaľko in 2024 described the use of FG5-215 and FG5X-251 instruments and the gradual improvement of measurement methods and uncertainty assessments. The authors related the data to a reference function maintained with the help of the superconducting record at Pecný. They also reported observations performed within a formally recognised metrological framework, with a stated uncertainty of 2.2 microgals for relevant absolute measurements. This figure should not be mistaken for a universal precision of all gravity stations or all periods. It describes a specific traceability and measurement arrangement, and its meaning depends upon the conditions under which the uncertainty was assessed. The work nevertheless showed how a programme begun as national

network modernisation had developed into internationally relevant metrological research by 2025.

Not all improvements in gravimetry occurred at the observatory. Large-area gravity mapping remained important because detailed variations in the field could not be inferred from a small number of exceptionally accurate stations. The Czech Geological Survey's databases and related national geodetic resources preserved results from systematic surveys undertaken before and after independence. These observations differed substantially in point density and reliability. The later, more detailed mapping carried out at approximately 1:25,000 scale occupied most, but not all, of the country's territory, while some remaining areas continued to depend on older and sparser surveys. At the end of 2018, one official description of the database distinguished roughly 304,000 detailed survey points from a smaller number retained from earlier national mapping. Figures of that sort describe the state and classification of a particular database, not the creation of an equivalent number of new stations after 1993. The modern achievement was the ability to evaluate their suitability for new gravity-field applications.

In 2023, Martin Lederer and Otakar Nesvadba examined the need to densify gravity observations for geodetic purposes. Their account identified a substantial contrast between approximately four-fifths of Czech territory covered by detailed mapping and remaining areas where older measurements were too sparse for the highest demands of quasigeoid determination. The article explained that a finer numerical grid cannot compensate for deficient underlying observations. Interpolating gravity between distant stations may produce a smooth surface without capturing real small-scale changes in the field. The densification programme, whose field measurements had been completed by 2022, sought to improve gravity information where errors in terrestrial data limited accurate vertical transformations. It was therefore a continuation of classical field surveying in response to contemporary satellite-geodetic requirements, rather than evidence that satellite technology had made ground-based measurement obsolete.

The accuracy of a gravity point depends upon the quality of its position and height as well as the measured acceleration. An error in elevation affects reductions of gravity to a reference surface, and a location error may be important in mountainous terrain where anomalies change rapidly. Surveyors also need information about instrumental calibration, the vertical gravity gradient and the procedure used to connect detailed observations with reference stations. As national datasets were brought into digital form, inconsistencies that had been tolerated in paper-based cartography became visible in numerical comparisons. Modernisation consequently required metadata, documented revisions and procedures for identifying outliers. The research undertaken by geodetic and geological organisations showed that the scientific value of a national gravity map lies not only in its point density but also in the ability of later users to reconstruct how each value was obtained.

The connection between gravity measurement and height became the central practical achievement of Czech physical geodesy. The Bpv system provides normal heights that cannot be identified directly with the ellipsoidal heights returned by GNSS positioning. Their relation includes a height anomaly, the separation of the reference ellipsoid from the quasigeoid

associated with the terrestrial gravity field. Across the Czech Republic this separation is measured in tens of metres and varies with location. To obtain a useful physical height, the satellite observation must therefore be accompanied by an adequate model of that variation. Distinguishing a quasigeoid from a geoid is not merely a matter of terminology. The two surfaces correspond to different theoretical constructions and height systems, and a precise transformation requires consistency between the surface used and the convention by which the reported height was defined.

The quasigeoid model CR2000 represented an important early response to this problem. Researchers combined digitised gravity maps, topographic information and a global geopotential model to estimate the field on a national grid. A remove-and-restore strategy separated broad planetary components from the residual field that local data could resolve more effectively. Numerical methods involving the Stokes integral and a fast Fourier transform helped calculate a detailed gravimetric surface. The result was then adjusted using comparisons between GPS-derived ellipsoidal heights and levelling observations at selected benchmarks. In the international geoid repository, the model is described as having been checked against 532 independent GPS/levelling points, with a standard deviation of approximately 3.4 centimetres. That assessment provided an empirical measure of its usefulness while also revealing the residual limitations of the available observations and modelling assumptions.

The 2004 publication by Jan Kostelecký and his collaborators in Studia Geophysica et Geodaetica placed the Czech work on quasigeoid determination into the international literature. Its title, Quasigeoids for the Territory of the Czech Republic, reflected a programme of comparing computed gravity-based surfaces with observations that used an independent measurement principle. This relationship between calculation and validation was crucial. A model adjusted to one set of GPS/levelling stations might fit those points well while remaining uncertain elsewhere, particularly in mountainous or poorly surveyed regions. A convincing national model therefore required tests at control sites that had not been used to construct it. The work illustrated how a state-specific engineering requirement could also generate a scientific contribution to the wider discussion of regional gravity-field modelling and the choice of appropriate numerical and observational constraints.

The later CR-2005 quasigeoid model incorporated a larger set of terrestrial controls. The International Service for the Geoid describes it as a gravimetric solution rectified with GPS/levelling observations at 1,024 points, represented on a grid of one minute in latitude and one and a half minutes in longitude. It served the practical need to transform between the European terrestrial frame and the Czech physical height system. The model’s value was not that the gravity field had suddenly been determined everywhere to the resolution of the displayed grid. Rather, it provided a consistent, documented representation whose residual discrepancies could be evaluated against known checkpoints. Its adoption in national geodetic procedures brought an advanced result of physical geodesy into routine measurement practice. It also created a benchmark against which the benefits of new gravity observations, improved digital terrain models and later computation methods could be tested.

The detailed quasigeoid developed by the Land Survey Office, known as QGZÚ, marked a further stage in national modelling. The 2013 version drew together improved terrain and gravity information to support transformations between the Bpv and ETRS89 height descriptions at the centimetre level in suitable conditions. Its development exposed a problem familiar in all high-resolution geoscience: a model may be highly satisfactory for normal applications while remaining limited by systematic gaps in its most demanding input datasets. Research on the subsequent densification of gravimetry was partly motivated by the prospect of improving the model to the level of a centimetre or better over a larger proportion of the territory. This did not imply that every point measured with GNSS would yield a physical height of such quality. Observational errors, local changes in the benchmark, transformations between reference frames and the effect of unmodelled terrain features remained relevant to the accuracy of any particular result.

High-resolution gravity-field determination also raised questions about terrain reduction. A mountain produces a gravitational effect that must be estimated if observations made at different elevations are to be compared meaningfully. Yet the relationship between a digital terrain model and actual subsurface mass is never exact. The computation requires a choice of density and a description of the land surface adequate for the spatial scale of the problem. Czech geodesists working on mathematical gravity modelling investigated methods for evaluating terrain contributions and the errors introduced by approximation. These studies had international relevance because mountainous surveys elsewhere face the same trade-off between computational complexity and neglected detail. Advances in computing widened the range of possible calculations, but did not eliminate the need to justify the assumptions by which the gravitational attraction of real, heterogeneous terrain was represented.

Pavel Novák's work on gravitational-field modelling supplied an important theoretical dimension to these developments. His publications examined the use of harmonic series, local gravity data, mathematical inversion and precise terrain effects in the determination of the field. A 2010 review in Surveys in Geophysics addressed high-resolution constituents of the Earth's gravitational field, and another article that year examined direct modelling through harmonic series. The research connected potential theory to the practical problem of combining observations with different spatial coverage and resolution. Satellite measurements constrain broad and intermediate wavelengths, while terrestrial gravity and a reliable description of relief are indispensable for the shorter wavelengths required in regional applications. Choosing how to combine them is not a neutral technical step: it determines which features the resulting model can resolve and which errors may pass from one dataset into another.

Geodetic gravity modelling must also deal with the inverse nature of its central problem. Measurements of acceleration at the surface provide incomplete information about a potential field that extends throughout space, and many distributions of mass can be consistent with similar external observations. Classical techniques associated with Stokes, Molodensky and Helmert offer mathematically different ways of using gravity anomalies or disturbances to estimate reference surfaces. Their assumptions differ in how they treat the topography, the continuation of observations and the physical position of the data. The Czech contribution after

1993 included numerical studies of such choices, their stability and their sensitivity to errors. A calculation that can be performed on a computer is not necessarily reliable when the input observations are noisy or unevenly distributed. Theoretical analysis was therefore part of the infrastructure of precision, even though it was less visible than a new observatory instrument or a national network.

The appearance of improved global geopotential models made the interaction of local and planetary gravity information more productive. The EGM96 model offered a widely used description of long-wavelength and medium-wavelength gravity during the early years of Czech independence. EGM2008 subsequently provided much finer global representation and stimulated direct comparisons with Czech GPS/levelling and quasigeoid data. Novák, Jan Kostelecký and Jaroslav Klokočník examined how accurately such global products reproduced local information, rather than assuming that greater nominal resolution guaranteed better agreement. Where a national model performed better, the discrepancy could indicate the value of local gravimetry or of a more appropriate regional calculation. Where the global model agreed well, it offered an independent check on terrestrial observations. This dialogue between global and local models became an important feature of Czech physical geodesy.

The international gravity missions of the early twenty-first century expanded the objects of study still further. CHAMP, GRACE and GOCE enabled the Earth's gravity field to be examined from satellite motion or gradiometric observations, with differing sensitivities to the spatial and temporal structure of the field. Czech scientists, including Klokočník, Aleš Bezděk, Kostelecký and Novák, worked on aspects of orbital dynamics, gravity recovery, modelling and validation. Their contributions were not confined to applying satellite products over Czech territory. They examined the performance and interpretation of space-geodetic methods within international research, bringing national expertise in potential theory and geodetic computation to problems of planetary scale. The observational logic also changed: data recorded above the atmosphere could be compared with terrestrial networks to test how a model represented phenomena that no single observing platform could measure completely.

GRACE was especially important because its observations made variations in terrestrial mass distribution visible over time. Changes in the gravity field could reveal the combined effects of water storage, ice loss and other large-scale processes. At a local gravimetric station, similar causes might produce variations that were far smaller and more strongly affected by nearby conditions. Czech researchers were therefore concerned with the relationship between global monthly gravity solutions and the terrestrial records they maintained. Comparisons required attention to spatial resolution, filtering, reference conventions and the environmental signals retained in each product. It would have been misleading to expect the smooth satellite field to reproduce every variation registered by an instrument close to the ground. The achievement was instead to identify what the observations could jointly say about the distribution and movement of mass through the Earth system.

In 2013, Jan Kostelecký, Bezděk and Klokočník published an analysis of global and regional seasonal geoid variations detected by GRACE. They compared gravity-derived descriptions from different processing centres and considered seasonal changes in several regions, including the behaviour inferred at the Pecný observatory. Their work illustrated how the

apparent movement of a reference surface might be understood as a response to changing planetary mass distribution rather than as a permanent deformation of the solid ground. It also showed that results from distinct GRACE solutions required comparison and interpretation. The geoid was no longer only a static surface to be calculated once for a national map: modern satellite observations brought its time dependence into scientific view. This finding widened the intellectual scope of Czech physical geodesy beyond the immediate service of height transformation.

GOCE presented a different problem by using dedicated gradiometric measurements and precise satellite tracking to investigate fine details of the global gravity field. Czech participation in related European Space Agency research involved modelling orbital behaviour, assessing the recovery of gravitational information and applying the resulting geopotential models. The satellite's mission placed considerable demands on how the effects of Earth's non-uniform field were represented in orbital calculation. Collaborative work associated with the Astronomical Institute of the Academy of Sciences and geodetic researchers also examined the limitations introduced by orbital configuration and observation geometry. These questions link gravity determination with celestial mechanics. A satellite is not simply a carrier of a measuring device: its movement is itself evidence about the gravity field, and the mathematical interpretation of that evidence requires an exact account of forces, reference frames and the instrument's observational geometry.

Research on gravity and the Earth's rotation formed another link with astronomical science. The position of the rotation axis, the orientation of the Earth in space and variations in rotational behaviour affect the reference frames used by terrestrial and satellite geodesy. Czech investigations by Jan Vondrák and collaborators drew on long astronomical records and modern space-geodetic techniques to examine Earth-orientation parameters and the influence of atmospheric and oceanic processes. These studies cannot be reduced to a matter of coordinate housekeeping, because Earth orientation is itself a physical response to the movement of mass and angular momentum within the planet and its surrounding fluid envelopes. The connection matters whenever measurements made at different epochs or in different global systems are compared. It also demonstrates that the scientific measurement of the Earth extends from the gravimeter laboratory to the dynamics of a rotating body observed from space.

The transition from isolated projects to distributed research infrastructure strengthened these connections. The CzechGeo initiative, closely associated with the European Plate Observing System, drew together observations from seismic, GNSS, magnetic, gravimetric and geodynamic networks. Its participating institutions included Academy of Sciences institutes, universities, the Czech Geological Survey and the national geodetic research institute. The concept did not erase disciplinary differences; it made measurements more useful by preserving their specific meaning while improving access to complementary records. E.g., an episode of apparent ground movement could be investigated against nearby seismic observations, information about a gravity change and the history of the GNSS station. By the 2010s, the establishment and management of such linked infrastructures had become an important scientific activity. Their value depended on consistent time references, stable

station documentation and the ability of researchers to retrieve observations collected for different primary purposes.

Central European cooperation had already demonstrated the advantages of repeated geodetic monitoring in the 1990s. The Central European GPS Geodynamic Reference Network, established in 1994 after preparations beginning in 1992, brought investigators from several countries into a common programme for determining contemporary crustal motion. Czech specialists contributed observation sites, processing and geodetic expertise. Repeated campaigns between 1994 and 1997 provided information on station positions, velocities and the uncertainty of the resulting displacement estimates. Research published in 2000 in the Journal of Geophysical Research interpreted crustal movement and strain across a broad European area using those GPS records. The importance of the network was not a discovery of rapid motion everywhere. It was the establishment of comparable observations over a large region, permitting small movement rates to be analysed in relation to tectonic setting and the stability of the chosen reference frame.

The Bohemian Massif provided a particularly demanding test of the distinction between a tectonically quiet region and a region without observable movement. Its geological history is long, yet parts of western Bohemia experience earthquake swarms and local activity associated with fault systems. Since 1993, surveys in the West Bohemia–Vogtland region have combined satellite positioning, precise levelling, repeated gravity measurements and geophysical observations. Such combinations are valuable because the techniques respond differently to changing conditions. GNSS records displacement relative to a defined frame; levelling establishes differential heights between benchmarks; gravity detects changes in acceleration caused by both movement and redistributed mass. Where several kinds of measurement show compatible patterns, a geological interpretation becomes more plausible. Where they disagree, the difference can reveal local hydrology, unstable monuments or a weakness in the proposed explanation rather than an error that should simply be discarded.

Jan Mrlina’s 2000 study of vertical displacements in the Nový Kostel seismoactive area provided a concrete example of carefully designed monitoring. A precise levelling network established in 1994 was enlarged over successive campaigns and contained seventy points by 1999. The observations sought changes of only a few millimetres, a scale at which the stability of each benchmark and the statistical confidence of a height difference are critical. The investigation found spatially varied patterns of relative vertical change and considered their possible relationship with earthquake swarms. Such findings were important without being a definitive explanation of the underlying fault mechanics. A levelling route samples a surface response, while the geological source of that response lies at depth. The scientific advance consisted in making a previously difficult question observable and in recognising the limits of the inference that could be drawn from short measurement series.

Cross-border research in the Sudeten Mountains furnished a related history of gradual methodological refinement. Czech and Polish investigators established and repeated GPS campaigns in geodynamic networks, including sites in the eastern and western Sudetes, and compared the results with levelling and geological evidence. Vladimír Schenk, Zdeňka Schenková and colleagues examined whether inferred station movements were reliable when

observations were available only at discrete epochs. Their 2010 study of the East Sudeten network showed why statistical tests and realistic thresholds matter when interpreting the apparent motion of individual sites. A difference between two coordinates may be visually persuasive on a map yet fail to establish a significant velocity. The research addressed the necessary distinction between an estimated displacement, its uncertainty and a geologically meaningful movement pattern. It also demonstrated the value of long-term cooperation across a border traversed by the same geological structures.

Other campaigns in Moravia and adjoining regions widened the spatial scope of Czech geodynamics. The Morava geodynamic network, begun in the early 1990s, combined the resources of Czech technical universities and collaborators able to provide GPS equipment and processing facilities. Later investigators returned to selected points, compared new positions with earlier campaigns and supplemented satellite observations with local levelling where the character of vertical motion required closer scrutiny. This work was especially demanding because a change in surveying technology across decades could introduce an apparent shift unrelated to crustal movement. The position of a monument, the epoch of coordinates, satellite reference systems and the treatment of observation errors therefore had to be reconstructed before differences were attributed to natural processes. The resulting investigations were as much exercises in scientific continuity as attempts to estimate present-day crustal motion.

Geodynamic interpretation also required attention to effects caused by human activity and near-surface processes. Mining, groundwater extraction, construction and changes in soil moisture can produce local deformation or gravity variation without representing broad tectonic movement. In some industrial and mining landscapes of the Czech Republic, engineering monitoring needed to distinguish ground subsidence from regional geodynamic trends. Gravity surveys could assist investigations of underground structures or changes in mass distribution, but a gravity anomaly by itself could not uniquely determine the geometry and composition of its source. The same limitation applies when a levelling benchmark in a disturbed area appears to move. Understanding the history and stability of the site is essential before using that observation as evidence about the movement of an entire crustal block. These difficulties encouraged Czech teams to compare geodetic measurements with geological and environmental information rather than interpreting each instrumental series in isolation.

By the middle of the 2020s, Czech physical geodesy combined several kinds of scientific achievement. At Pecný, an observation series supported research on terrestrial gravity, tides, hydrology and the reproducibility of absolute measurements. Across the country, gravimetric databases and models of the quasigeoid linked mathematical potential theory with the everyday determination of heights. Satellite research connected Czech scientists to analyses of planetary mass redistribution and global gravity-field missions. Geodynamic networks in western Bohemia, the Sudetes and other regions made it possible to investigate local movements against a broader tectonic background. These achievements depended on institutions with different mandates, but their strongest results emerged from compatibility among the data. The field’s development was therefore characterised less by the replacement

of one technique with another than by increasing integration among instruments, models, observational histories and reference systems.

This record also makes the limits of measurement a central historical theme. A national quasigeoid may reproduce selected height observations to centimetre precision while remaining weaker where gravity mapping is sparse. A gravimeter may detect changes of a few microgals while the cause of those changes is uncertain because soil water or atmospheric loading has not been adequately represented. Repeated GNSS and levelling observations may reveal a plausible displacement whose significance depends upon the stability of the monument and the length of the record. Czech researchers increasingly treated such limitations as explicit components of their results. By 2025, the scientific measurement of the Earth in Czechia had acquired a richer meaning: it required not only precision in determining a value but also a defensible explanation of what that value represented, which processes could have changed it and how another investigator might test the conclusion.

Precise Positioning, Deformation Monitoring and the Interaction between Geodetic and Atmospheric Research

In the Czech Republic, the history of precise positioning after 1993 cannot be separated from the history of changes that positioning made observable. A receiver established beside a motorway, on a mountain ridge or above a mine shaft may be used to determine a coordinate, but the same instrument can also reveal that the coordinate is not fixed. Its antenna moves with the ground, its measurements respond to changing atmospheric conditions, and its accuracy depends upon a chain of observations extending far beyond the site itself. Czech geodesists increasingly treated these effects as connected subjects rather than unrelated sources of correction. Between independence and 2025, the country developed a combination of national positioning services, specialised geodynamic networks and scientific methods for retrieving information about water vapour from satellite signals. The resulting work linked cadastral and engineering applications with geology, geophysics and meteorology. Each inference nevertheless required its own uncertainty assessment.

The point of departure in 1993 was not a blank technical landscape. Czechoslovak surveying institutions had maintained precise levelling routes, triangulation points, astronomical observations and deformation measurements at selected engineering and geological sites. Yet their original reference systems, instruments and processing routines were not designed for a world in which continuous satellite observations could be compared across national borders each day. The creation of the Czech Republic gave the inherited geodetic infrastructure a new administrative setting, while the expanding Global Positioning System offered ways to improve both national positioning and scientific measurement. During the 1990s, surveyors had to learn how to maintain continuity with established national coordinates without treating them as immutable physical quantities. A small discrepancy might reflect a reference-frame transformation, movement of a monument or observational error. A credible interpretation

required knowledge of the observing history as well as a mathematically accurate coordinate transformation.

Precision acquired a different meaning according to the problem being investigated. A cadastral survey normally requires coordinates consistently related to legally recognised boundaries. An engineer assessing a viaduct may be interested primarily in whether adjacent points have moved relative to one another during a specific period. A geophysicist investigating a fault needs displacements expressed in a stable and explicitly defined terrestrial reference frame, often over many years. Meteorologists, meanwhile, can use the delay of the same satellite signal to infer the changing condition of the lower atmosphere. A software-generated accuracy figure cannot alone establish success. Instrument calibration, antenna installation, observation duration, monument stability and the interpretation of a time series may prove more important than an extra decimal place. Czech research after 1993 became increasingly attentive to these differences between repeatability, absolute accuracy and reliability for a particular scientific or practical purpose.

The expansion of continuously operating Global Navigation Satellite System stations changed the scale of observation. Early campaign measurements required researchers to assemble receivers, occupy predetermined points and return after a suitable interval to calculate displacement. Permanent stations accumulated a record that could reveal seasonal fluctuations, sudden offsets, equipment changes and longer-term trends. Their usefulness depended on rigorous metadata: the dates of antenna replacements, receiver firmware changes, local construction work and interruptions in power or telecommunications. The Geodetic Observatory Pecný became a particularly important institutional bridge between national surveying and international geodesy. Through its contribution to European and global GNSS analysis, Czech researchers gained access not merely to more satellite signals but to better estimates of satellite orbits, clocks and station positions. This improvement in external reference information transformed what could be inferred from movements of a local monument and from differences in travel time between satellite and receiver.

The development of positioning services also altered the geography of practical precision. The Czech national permanent station service, CZEPOS, began operation in 2004 and subsequently supplied differentiated services for surveying, construction, agriculture and other professional users. Its facilities allowed receivers in the field to use correction information generated from permanent stations rather than depending entirely on a local base installed for each assignment. The network’s scientific relevance extended beyond the convenience of faster positioning. It supplied regularly observed positions tied to the national implementation of European reference systems and enabled repeated checks on the stability and quality of the spatial framework. Network geometry, distribution of stations and cross-border compatibility determined whether a correction could be applied consistently near mountain frontiers or in regions where the distance to the nearest station was large. The service connected operational geodesy with research on systematic error.

Real-time kinematic positioning became an increasingly familiar technique in this environment. By analysing carrier-phase observations from a rover and one or more reference stations, RTK systems can resolve ambiguities and provide centimetre-level results under

suitable conditions. Network methods extend the effective area of a correction by estimating spatial variations in satellite, ionospheric and tropospheric errors. A virtual reference station represents one practical way of distributing this information to the user. Such terminology can give an impression of automatic accuracy, however, that the evidence does not justify. Radio interference, vegetation, an obstructed horizon, multipath reflections and incomplete ambiguity resolution may undermine a nominally precise result. The Czech experience showed that reliable positioning services require continuous quality control, not only the installation of antennas. The Surveying Office's documentation by 2025 distinguished differential GNSS, RTK and virtual-reference-station services, making their different expected levels of accuracy explicit rather than presenting them as interchangeable products.

Whereas network RTK relies upon nearby infrastructure, precise point positioning uses highly accurate satellite orbit and clock information to estimate a receiver's position with relatively limited dependence on local reference stations. Developing practical PPP algorithms required progress in the handling of code and carrier-phase observations, clock parameters, phase ambiguities, ionospheric effects and the neutral atmosphere. Czech researchers at Pecný took part in this transition, especially through the work of Jan Douša and Pavel Václavovic. PPP exposed parameters formerly reduced through differencing and enabled their simultaneous estimation. When a method could obtain precise coordinates, receiver-clock corrections and tropospheric delays in the same solution, geodesy ceased to have a single narrowly defined product. The combination became particularly useful when rapid atmospheric estimates and high-quality positions were required from the same station.

One substantial obstacle in this work was the time needed for a new solution to become reliable. The initial carrier-phase ambiguities cannot ordinarily be assumed known, and their estimation may be affected by the receiver's movements or changing satellite visibility. Precise positions computed immediately after an interruption are not necessarily comparable with those derived from a stable long observation interval. Czech investigations into filtering, smoothing and the use of real-time orbit and clock products sought to improve both responsiveness and analytical consistency. The G-Nut software family developed at Pecný became an important vehicle for such work, with specialised tools for quality checking and precise positioning. Methodological contributions lay in examining the behaviour of processing strategies under changing conditions and demonstrating how an operational technique could be adapted for scientific estimates. Fast estimates were valuable only if their limitations could be described and checked against higher-quality post-processed solutions.

Observation quality was accordingly treated as a measurable property of the entire system. A receiver might report an uninterrupted stream of positions although a change in satellite geometry, signal tracking or the surrounding reflective surfaces had shifted its statistical properties. Continuous GNSS monitoring therefore required checks on missing observations, cycle slips, signal-to-noise ratios, multipath and the consistency of individual constellations and frequencies. For a displacement study, such checks also help determine whether an apparent step in a position record is physical or instrumental. For atmospheric work, a change in receiver or processing model can introduce an artificial discontinuity into a delay series. The systematic quality assessment associated with Pecný's software research provided a

necessary counterpart to the growing density of reference stations. It helped ensure that improvements in measurement frequency were not mistaken for improvements in the credibility of scientific conclusions.

The benefits of international reference networks were visible most clearly when national observations were combined with measurements made elsewhere in Europe. A velocity estimated from a small Czech network is a relative quantity until its reference frame and constraints are defined. Reference stations in neighbouring countries make it possible to distinguish local movements from artefacts introduced by treating an unstable point as fixed. European Permanent Network stations, including those at Pecný and Brno, provided part of this framework, while the global services supplied orbit, clock and reference-frame products. The resulting records could support both applied positioning and investigations of crustal movement. Yet international integration introduced its own technical responsibilities. Changes in reference-frame realisation, antenna calibrations or processing conventions could alter the apparent movement of a station. Long-term comparisons therefore required reprocessing or careful harmonisation rather than simply joining together coordinates produced at different dates.

The growing number of satellite constellations added another dimension to the problem. GPS was joined in routine geodetic analysis by GLONASS, Galileo and, increasingly, other systems, which increased the availability and angular distribution of measurements. More observations can strengthen a solution in an obstructed setting and support the estimation of atmospheric gradients, but they also introduce constellation-specific clocks, inter-system biases and differences in signal characteristics. The technological change was therefore inseparable from improved mathematical modelling and software. Czech specialists worked within international efforts to monitor satellite-navigation performance and generate rapid orbit and clock estimates. By the 2020s, the multiplication of tracked signals had made high-precision positioning more robust in many circumstances, without eliminating the need for calibration, well-designed station environments and scrutiny of the models used to process data.

The relation between satellite positioning and the atmosphere is most easily understood as an effect that changes its role according to the question asked. Radio signals transmitted from navigation satellites do not travel to the ground at the speed they would have in a vacuum. Their passage through the neutral atmosphere is delayed by air pressure, temperature and, especially in the variable component, water vapour. For accurate positioning, the delay must be modelled or estimated so that it is not misinterpreted as an error in the receiver’s location. Once estimated carefully, however, it provides information about the atmosphere itself. Czech research at Pecný was notable for developing these two interpretations together. The desired output might be a corrected coordinate or a series of atmospheric parameters; in either case the reliability of one depended upon how well the other had been represented. A geodetic residual became a potential meteorological observation, but only after a sequence of assumptions and corrections had been tested.

The neutral-atmosphere delay is often described through a hydrostatic component and a wet component. The hydrostatic contribution can usually be estimated comparatively well when surface pressure and an appropriate model are available. The wet contribution varies more

rapidly because water vapour is not distributed evenly in space or time. GNSS solutions commonly estimate the combined zenith total delay and use modelling to separate components. When temperature information is available, the wet delay can help estimate integrated water vapour along the atmospheric column above a receiver. This retrieval is attractive because many permanent GNSS stations operate continuously, including during cloudy and rainy weather that can limit other observations. A single station, nevertheless, does not reveal the full vertical profile of humidity. Nor does an atmospheric delay directly measure rainfall. Czech investigations repeatedly returned to these distinctions, treating GNSS measurements as complementary observations whose usefulness improved when combined with radiosondes, surface measurements and numerical weather models.

A major institutional advance came through European cooperation on ground-based GPS meteorology. Participation in COST 716, the TOUGH project and the EUMETNET GNSS Water Vapour Programme connected Czech geodetic analysis with meteorological services that needed timely observations. Jan Douša's work at Pecný linked the production of satellite-derived atmospheric parameters to a broader European system for numerical weather prediction. These collaborations created practical demands that differed from conventional scientific processing. A result delivered days after an observing campaign might be appropriate for a detailed reanalysis but of little use to a forecaster preparing the next model cycle. Near-real-time delivery imposed requirements for automated data transfer, dependable processing and consistent quality indicators. The Czech contribution was thus partly algorithmic and partly organisational: an observing programme became a service through which geodetic products could enter meteorological workflows under documented conditions.

The operational relationship was not simply a matter of transferring numbers from one institution to another. A forecast model represents temperature, pressure and moisture on a finite 3D grid, whereas a GNSS receiver measures the aggregate propagation effect along particular lines of sight. To use the observation, a model must reproduce the quantity the receiver has estimated and take account of the uncertainty of both sources. Differences may reflect errors in the atmospheric forecast, but they may also arise from local geography, the treatment of receiver heights or an inconsistency in atmospheric parameterisation. Czech geodesists worked with meteorologists, including specialists at the Czech Hydrometeorological Institute, to make these comparisons more meaningful. The integration of GNSS estimates into modelling practice required a common language for observation times, vertical references, bias assessment and the significance of missing measurements. It was a research problem in data interpretation as much as an achievement in communications technology.

The geography of Czechia provided a demanding setting for such work. A comparatively compact national territory contains considerable contrasts between mountain ridges, enclosed valleys, uplands and lowland urban centres. Weather systems crossing this landscape can produce horizontal differences in humidity that a single regional mean would conceal. A receiver on a summit samples an atmospheric column whose lower boundary differs from that of a receiver in a nearby valley. Direct comparison of zenith delays without accounting for this elevation difference could create an apparent atmospheric gradient that is

partly geometric. Moreover, models with insufficient horizontal resolution may smooth out a localised moisture feature that is relevant to intense precipitation. Research on high-resolution tropospheric products drew upon this spatial complexity. It helped clarify why a network initially established for terrestrial positioning could provide information about atmospheric processes that ordinary station-by-station meteorological observations would not fully describe.

The GNSS4SWEC European cooperation programme gave these questions a more systematic experimental setting. A benchmark investigation led by Douša and colleagues, published in 2016, assembled GNSS observations and numerical weather model information for an eight-week period incorporating severe precipitation episodes in Central Europe. Its purpose was to develop and test advanced products such as rapidly updated zenith delays, horizontal gradients and delays along individual signal paths. The study documented cases in which GNSS-derived parameters revealed atmospheric spatial structure more finely than the numerical models used for comparison. It also examined the possible influence of hydrometeors, including cloud water and ice, on propagation delay during severe weather. The value of the benchmark was methodological: investigators could examine the same episode using comparable input data, rather than attributing disagreements to poorly documented differences in datasets or processing practice.

As these studies developed, horizontal tropospheric gradients became an increasingly important object of analysis. A zenith delay compresses information about the atmosphere into a value above the station. The gradient terms describe departures from azimuthal symmetry in the propagation effects of satellite signals arriving from different directions. Their estimation is technically demanding because errors in station coordinates, satellite geometry, multipath or processing strategy can influence the result. When properly constrained, however, the gradients offer an indication of directional structure in refractivity and the humidity field. The potential use in forecasting was especially relevant during the approach of fronts and localised rainfall systems. Czech scientists worked with colleagues abroad to assess whether such parameters could add independent information to numerical weather prediction. The answer depended upon the density of the network and the scale represented by the weather model, a qualification that prevented a potentially useful observation from being treated as universally beneficial.

The 2018 study by Douša, Václavovic, Lewen Zhao and Michal Kačmařík represented a significant step in real-time atmospheric processing. It presented an adaptable strategy for producing both real-time and near-real-time tropospheric parameters through precise point positioning, filtering and smoothing. Real-time orbit and clock information made it possible to estimate rapidly changing parameters rather than depend entirely on delayed final solutions. The researchers examined the relationship between timeliness, processing strategy and the precision of the products. Their work belongs to the history of exact positioning because tropospheric estimation is integral to the quality of the coordinate solution. Equally, it belongs to atmospheric research because a GNSS station can become a continuous monitor of changes in the signal path. This dual purpose helps explain why software developed in a

geodetic observatory became relevant to a meteorological community concerned with rapidly changing conditions and severe weather.

The collaboration was extended in research published in 2019 by Florian Zus, Douša, Kačmařík, Václavovic and colleagues. The investigators developed procedures for assimilating zenith delays and horizontal delay gradients into a numerical weather model. Their experiments distinguished a single station from a dense network. In the sparse case, directional information could improve the reconstructed refractivity field beyond the contribution of the zenith delay alone. In a dense network, neighbouring zenith observations already contained much of the horizontal information, so the additional benefit of gradients was smaller. The study also demonstrated the usefulness of processing real data with the G-Nut/Tefnut software. It did not establish that assimilation of every available gradient would improve every forecast. Its contribution was a clearer understanding of the conditions under which complex GNSS products could add value, and of the scale-dependence that must be considered when interpreting the results.

European assessment of real-time tropospheric monitoring continued into the 2020s. A 2021 publication by Douša, Václavovic, Petr Bezděka and Guergana Guerova compared conventional near-real-time network processing with real-time precise point positioning and described a production system extending to roughly two hundred stations across Europe and beyond. The contrast concerned more than a shorter delay between observation and delivery. Frequent estimates of zenith delay and horizontal gradients could help identify evolving atmospheric asymmetry, while final solutions remained important as independent standards for validation. Comparing collocated stations and processing modes showed how the performance of an operational product could be assessed. The research also reflected a general movement in Czech geodesy from the occasional measurement campaign towards persistent computational services. These services required sustained technical responsibility, especially where their products might influence external scientific or public operational systems.

The possibility of using GNSS observations to investigate climate introduced longer time scales and stricter continuity requirements. A meteorological event might be interpreted through changes over minutes or hours; a climatic trend may be inferred from observations covering years or decades. Instrument replacement, recalibration, antenna changes or alterations in processing strategy can resemble a small atmospheric trend if they are not adequately documented. A longer dataset is therefore not automatically a better climate dataset. European reviews involving Douša considered the future of GNSS meteorology in forecasting, nowcasting and climate studies, drawing attention to reprocessing and data homogeneity. Czech stations could contribute to these analyses because of their long observing histories and links to European reference infrastructure. Their contribution depended on the careful treatment of discontinuities as much as on the physical durability of the instruments. Stable reference data and stable scientific interpretation were related achievements, but neither could be assumed from continuous operation alone.

The atmospheric component also complicated the interpretation of deformation records. A station whose vertical coordinate appears to rise or fall over several months might be

responding to an imperfectly estimated wet delay, seasonal loading or changes in local monument conditions rather than tectonic movement. The vertical component of GNSS positioning is especially sensitive to correlations with tropospheric parameters. Analyses of geodetic time series therefore benefited from explicit estimation of atmospheric effects, comparison with numerical weather products and an examination of annual cycles. Conversely, an unexplained coordinate variation could be an indicator of deficiencies in the atmospheric modelling. Czech research progressively placed these competing explanations within the same analytical framework. It became insufficient to fit a straight line to positions and call its slope crustal velocity without testing possible discontinuities, environmental loading and the station's physical construction. This discipline of interpretation was essential when the annual movements under investigation were very small.

The West Bohemian earthquake-swarm region supplied a particularly demanding example. Around Nový Kostel, recurring seismic sequences occur within an area also investigated for volcanic and deep fluid-related processes. The Institute of Geophysics of the Czech Academy of Sciences established the WEBGEODYN geodetic network in 1993 to study the deformation of the surface. Its monitoring combined repeated satellite positioning with precise levelling, giving investigators the opportunity to compare horizontal and vertical behaviour. The network's design was centred on the principal earthquake-swarm area, with monuments distributed both inside and outside the zone of greatest interest. This was not a straightforward case of a large plate-boundary displacement readily visible after one survey. The scientific task was to detect small variations in a relatively stable intracontinental setting and determine whether they related to seismic activity, longer-term deformation or measurement uncertainty.

Monument design was integral to the West Bohemian programme. WEBGEODYN points were secured by substantial steel-pipe constructions and designed to permit repeatable antenna centring. Such practical details mattered because annual campaigns could otherwise record a change in the instrument's position on the monument rather than a change in the ground beneath it. The network included a mixture of inner and outer points and baselines extending over tens of kilometres. Researchers initially conducted repeated campaigns, but a more selective approach was adopted after 2009 as permanent observations became increasingly important. A permanent station began operating in the area in 2006, with subsequent changes to the station infrastructure in 2013 and the addition of a further permanent installation in 2018. The resulting combination illustrates a common research compromise: fixed continuous stations supply temporal detail, while the wider campaign network provides a denser spatial view of a geological structure.

The interpretation of observations in this region required close cooperation with seismologists. Earthquake catalogues establish when and where faulting-related events occurred, but an earthquake swarm does not necessarily produce an easily resolved permanent surface shift at every GNSS site. A temporary signal might be hidden by atmospheric disturbances, while a gradual movement might be difficult to separate from the accumulated effects of many small events. The local WEBNET seismic network supplied a complementary observational record, allowing geodetic behaviour to be considered in the light of the timing and distribution of seismicity. Czech researchers thus addressed a problem broader than the measurement of

coordinates: they sought physical consistency between processes inferred from separate instruments. A persuasive tectonic interpretation needed to withstand comparison with geological structure, earthquake distribution, precise levelling and the reference-frame assumptions made during GNSS processing.

Another line of work developed across the Sudetes and the eastern part of the Bohemian Massif. Czech and Polish teams constructed regional networks to investigate recent movement along major fault systems and among geological blocks. The EAST SUDETEN and related GEOSUD observations combined repeated GPS campaigns with geological and geophysical information. Research by Vladimír Schenk, Zdeňka Schenková and collaborators examined the reliability of velocities inferred from successive observation epochs. A 2010 study showed the importance of network geometry, observation duration and statistical thresholds before classifying a small apparent displacement as meaningful. These issues were particularly consequential near a national border where the structures being investigated continued into Poland. A geologically coherent observation system could not be confined to the Czech side merely because surveying institutions had historically managed data within separate jurisdictions. The gain came from geologically informed station placement and explicit tests of processing sensitivity.

Moravia provided a different but related field of investigation. The MORAVA geodynamic network was used to analyse the contact zone between major geological units and to assess movement tendencies around the Boskovice Furrow and neighbouring faults. A study published in 2017 by Lubomír Pospíšil, Otakar Švábenský, Pavel Roštínský, Eva Nováková and Josef Weigel drew upon about two decades of repeated measurements and confronted GNSS results with seismic, geomorphological and levelling evidence. The investigators discussed zones showing movement tendencies rather than claiming that every measured difference had a single tectonic explanation. This approach helped distinguish a geodetic anomaly from a geological conclusion. Local subsidence linked to old mining activity, movements in shallow deposits and changes in surveying conditions can coexist with regional fault-related processes. Recognising these alternatives made deformation monitoring a more useful contribution to earth-science interpretation and to the assessment of potentially unstable ground.

The relationship between GNSS coordinates and deformation could also be investigated through satellite radar interferometry. Synthetic aperture radar measures the phase of signals reflected from the Earth's surface, and suitable repeat observations can reveal changes in the distance between the satellite and a stable reflector. InSAR therefore provides spatially extensive information that is not obtained from a sparse set of geodetic monuments. Its central limitation is equally important: the observed change is principally along the radar line of sight, and the quality of an estimate depends on coherence, atmospheric effects and the interval between acquisitions. Surface vegetation, steep gradients in displacement and changes in land cover can destroy the phase information required for reliable interpretation. Czech researchers working in mining and geoinformatics explored these limits rather than treating radar images as direct maps of 3D movement. Comparisons with levelling and ground

observations remained essential to determine the magnitude and character of actual deformation.

The Ostrava–Karviná industrial district offered a major test of radar-based monitoring. Deep coal extraction had reshaped the physical landscape and produced subsidence affecting settlements, infrastructure and areas of reclaimed land. The problem was not merely the presence of a depression visible on a topographic map. Investigators needed to determine whether deformation was continuing, at what rate and over which parts of the mining landscape. Milan Lazecký and Eva Jiránková examined the use of satellite interferometry around the Lazy plant of the Karviná mine in a 2013 paper. Their assessment drew attention to the difficulty of detecting rapid and large subsidence with the radar systems then available, as well as to loss of coherence over vegetated surfaces. The result was a careful statement of capability rather than an unconditional claim of technological superiority. Interferometry was valuable for defining and studying deformation patterns, but fast changes still demanded complementary observations and appropriate temporal sampling.

The introduction of freely available Sentinel-1 radar observations expanded the scope of deformation mapping. A 2020 study led by Lazecký and involving colleagues at IT4Innovations and other institutions presented the IT4S1 system for automated interferometric measurements over Czechia. Its significance lay not only in processing individual scenes but in building a repeatable computational workflow capable of investigating change over a national area. A method that could be applied systematically was better placed to identify areas requiring further investigation than an isolated research image covering one coalfield. Yet the distinction between a screening product and a verified ground-displacement estimate remained important. Interferometric time series can contain atmospheric artefacts, decorrelation and errors related to the reference point. Interpreting a signal near a mine, landslide or urban structure therefore required geographical knowledge and independent evidence. The Czech contribution joined high-performance computing to the older discipline of measurement validation.

Combining ground-based and radar observations also revealed why deformation monitoring is necessarily multiscale. GNSS can supply an absolute or well-referenced 3D position at a limited number of points, while InSAR can indicate relative line-of-sight movement across broad surfaces. Levelling supplies highly sensitive information about differences in height along a route, and total stations or other engineering instruments can measure the relative movement of selected components of a structure. No one method satisfies every spatial and temporal requirement. A network designed for a few centimetres of rapid mine subsidence differs from a network intended to detect an annual millimetre-scale tectonic trend. Czech investigations exploited these differences through comparisons between measurement techniques. The aim was not to force every source into a single apparent displacement value but to identify what each could establish and where uncertainty prevented a confident interpretation. This concern became especially important as automated satellite products increased in volume and apparent completeness.

Engineering and heritage monitoring constituted a further branch of precise geodetic work. A notable study published in 2010 by Jaromír Procházka, Jan Záleský, Tomáš Jiřikovský and Jan

Salák described long-term stability measurements in the Prague Castle area. The research combined precise surveying, measurements of cracks and inclinations, observations of temperature and other environmental factors, and the assessment of dynamic effects from traffic and nearby tunnelling. Historic structures posed unusual difficulties because foundations, building materials and earlier alterations could not always be reconstructed with certainty. Measurable displacements also had to be interpreted in relation to the normal thermal and moisture-related behaviour of the fabric. The researchers linked their results to geotechnical and structural analysis rather than presenting surveying records as self-explanatory. Their work demonstrated that geodesy could contribute to the conservation of cultural heritage precisely by acknowledging the many physical processes affecting a monument.

The same principles applied to dams, bridges, tunnels and slopes, although each demanded a monitoring design adapted to its likely modes of failure. Measurements at a stable reference point outside a potentially moving structure have a different meaning from measurements within the structure itself. A bridge deck may expand daily with temperature, a dam may respond to changing reservoir levels, and a slope may accelerate after prolonged rain. A survey taken without corresponding environmental observations risks attributing an ordinary response to damage, or overlooking a developing process hidden beneath seasonal variation. Czech engineering geodesy therefore developed alongside geotechnics, structural mechanics and applied geology. Surveying was increasingly incorporated into systems that combined automatic sensors, repeated site inspection and physical modelling. The scientific question was whether movement exceeded its expected range under known conditions. That distinction is indispensable when using precise data to support decisions affecting infrastructure and public safety.

The treatment of uncertainty became more demanding as measurement systems accumulated data at shorter intervals. A large GNSS time series may be strongly correlated in time, so the conventional assumption of independent errors can give misleadingly narrow confidence intervals for an estimated trend. Seasonal signals may reflect hydrological loading, temperature-dependent monument behaviour or atmospheric processing effects. Sudden steps may result from an earthquake, a change of antenna or disturbance of the foundation. Czech researchers working in geodynamics and precise processing had to examine such alternatives before concluding that a displacement was permanent. The distinction between precision and accuracy remained particularly important for vertical positioning, where an excellent internal fit may coexist with a systematic tropospheric bias. Over the longer period, methodological advances involved better error models, explicit documentation of station histories, and comparisons among independent techniques. The availability of a continuous signal strengthened interpretation only when these forms of control accompanied the observations.

High-rate positioning introduced a different challenge: whether short-lived displacements could be identified rapidly enough to describe an event while it was unfolding. Faster GNSS sampling can help detect rapid motion during an earthquake or deformation of an engineering object, but a high frequency of coordinate estimates is not equivalent to high accuracy at every

epoch. Clock modelling, signal reflections and receiver behaviour can produce rapid fluctuations that superficially resemble true motion. Some Czech participation in internationally coordinated research, including the G-SEIS project concerned with GPS surface deformation within seconds, explored the scientific potential of such observations. The relevance to the Czech Republic was not confined to rare large earthquakes, since local seismic swarms and engineered structures also pose questions about temporal resolution. The research direction reflected a wider shift from observing average movement between surveys towards investigating the timing, duration and physical sequence of deformation. It remained necessary, however, to test whether the temporal resolution was supported by credible measurement precision.

By the late 2010s, the expansion of CzechGeo and connections with the European Plate Observing System placed local geodetic work within a broader framework for research infrastructures. The aim was to make long-running geophysical observations more accessible, better documented and more compatible with other disciplines. The West Bohemian geodetic network was one of the programmes associated with this development, while geological, seismic and other geophysical datasets supplied essential context. For a fault or subsidence study, a position series becomes more valuable when its monument history, instrument metadata and processing methods can be examined alongside the geological evidence. International cooperation also improves the capacity to detect errors specific to one centre or one analytical convention. This form of scientific infrastructure is not as conspicuous as a new satellite or a novel processing algorithm, but it is fundamental to reproducibility. The Czech experience illustrates the value of preserving older measurements while developing methods for their reanalysis with contemporary reference frames and environmental information.

The rapprochement between geodesy and meteorology produced a related demand for accessible, well-characterised data. A forecast model can make use of GNSS atmospheric products only when their delivery times, units, reference conventions and uncertainties are sufficiently consistent. Research comparisons similarly depend on being able to identify the processing version used to produce a delay series and the numerical weather model against which it was evaluated. The 2016 Central European benchmark and subsequent work on real-time products made these requirements visible. They also showed why the impact of an atmospheric parameter should be judged through controlled experiments rather than inferred from the quantity of available observations. A new processing technique may yield a clearer description of water vapour without necessarily improving every forecast. Conversely, a relatively modest improvement under a well-specified set of conditions can be a significant methodological achievement when the parameters can be reproduced and assessed independently. Such qualified results gave Czech interdisciplinary contributions their scientific durability.

The geographical distribution of research expertise shaped these developments. At Pecný and the Research Institute of Geodesy, Topography and Cartography, specialists developed precise processing, reference information and atmospheric products. The Surveying Office sustained the national positioning infrastructure on which many applied activities depended. At the Czech Technical University in Prague and Brno-based technical institutions, engineering

geodesy and the analysis of spatial measurements linked surveying with the behaviour of structures and terrain. The Institute of Geophysics and the Institute of Rock Structure and Mechanics of the Czech Academy of Sciences maintained field programmes in tectonically and geotechnically significant areas. VŠB–Technical University of Ostrava contributed research on geoinformatics, satellite radar processing and mining-related ground movement. These roles were not isolated compartments. Scientific progress frequently occurred where data, methods and personnel crossed institutional boundaries, enabling a result developed for one purpose to improve understanding in another field.

By 2025, precise positioning and deformation monitoring had become closely related branches of an increasingly interdisciplinary Czech geodetic science. National GNSS infrastructure provided dependable spatial reference and supported practical work; permanent and campaign observations supplied evidence of slow and rapid ground movements; radar interferometry extended monitoring across larger areas; and atmospheric analysis turned a positioning error source into information relevant to weather forecasting. The achievements were substantial, yet their common lesson was caution in inference. An observed coordinate change is not automatically tectonic movement, a radar fringe is not a direct 3D displacement, and a GNSS delay is not a vertical profile of humidity. Each result acquires physical meaning only through appropriate models, reference frames, independent measurements and transparent uncertainty estimates. The distinctive Czech contribution was to develop these capabilities within a comparatively compact country whose mountain landscapes, earthquake-swarm region, mining districts and urban heritage posed sharply different problems. Over three decades, the same measurement infrastructure came to serve scientific questions that its original designers could scarcely have combined in one observing programme.

Major Geodetic Achievements, Research Centres, Leading Scientists and Landmark Publications

The scientific achievements of Czech geodesy between 1993 and 2025 are best understood through the measurements that could be repeated, the reference systems that could be maintained and the questions that became answerable once observations from different institutions were brought together. A permanent receiver at Pecný, a gravimeter housed in a controlled laboratory and a line of levelling benchmarks across an industrial region produce very different evidence, yet all depend upon an agreed account of position, height and change. The Czech contribution was not confined to the acquisition of more sensitive instruments. Researchers developed methods of analysing incomplete and noisy data, strengthened international exchanges of observations, and made the results useful beyond the surveying profession. Their work provided foundations for studying the gravity field, crustal motion and atmospheric water vapour. It shows how specialised research can flourish within a small national scientific system.

The institutional setting was distinctive from the outset. The Research Institute of Geodesy, Topography and Cartography, generally known by its Czech abbreviation VÚGTK, retained a remit covering fundamental geodesy, measurement science and selected practical needs of the state's surveying administration. The Czech Office for Surveying, Mapping and Cadastre, or ČÚZK, and the Land Survey Office maintained the national geodetic foundations and their connection to administrative and mapping functions. Universities educated the specialists who developed and tested new methods, while institutes of the Academy of Sciences studied deformation, seismicity and the forces acting on the crust. The work of these organisations was complementary rather than interchangeable. A national reference frame had to be authorised and usable in practice, but deciding whether it was sufficiently stable required physical modelling, careful observations and independent scientific assessment. That relationship between responsibility for an operational system and freedom to investigate its limitations shaped much of the period.

The Geodetic Observatory Pecný, near Ondřejov, supplied the most conspicuous continuity between Czech geodetic traditions and the satellite era. It combined an established geophysical observing site with the analytical capabilities of VÚGTK, thereby placing satellite positioning, gravimetry, astronomical observations and geodetic metrology within a shared research environment. Its value was not simply geographical proximity to Prague or the presence of equipment. Continuous observing makes it possible to distinguish a temporary disturbance from an enduring change; maintaining the history of instruments permits a new observation to be compared with an earlier one. In September 1993, the GOPE station began permanent GPS observations, and in the following years its data entered the International GNSS Service and the EUREF Permanent Network. These steps placed a Czech site within a continental and global framework in which the accuracy of a local position could be evaluated against measurements obtained far beyond national borders.

Jan Kostelecký was among the scientists who helped carry Czech space-geodetic research across the change of political and technological regimes. His work connected satellite observations, the geometry and gravity of the Earth, and the practical question of how different reference frames could be realised. In collaboration with colleagues from Czech institutions and abroad, he participated in studies of terrestrial positioning, quasigeoid determination and gravity-field interpretation. The importance of this body of work lies partly in its span: calculations designed to improve a local height can draw on the same mathematical understanding of the potential field as research using satellite orbits to detect larger structures. Kostelecký's published contributions and institutional involvement therefore illustrate the continuity of a research school rather than a succession of unrelated projects. They also show how Czech geodesy retained a strong intellectual connection between physical geodesy and the measurement systems used by surveyors.

The 1990s brought a major change in the scale and frequency at which position could be determined. The traditional triangulation and precise-levelling networks remained essential, but periodic field campaigns were increasingly complemented by receivers capable of operating continuously. At Pecný, the GOPE record became a basis for time-series analysis, reference-frame maintenance and comparison with other European stations. Researchers had

to confront changes in antennas, equipment, signal environments and processing conventions. The installation of a receiver or the addition of another satellite constellation could improve the record while creating an artificial discontinuity if its effect was ignored. This led from a narrow concern with a coordinate at a particular date to a broader account of station behaviour and uncertainty over time. The methodological advance was to treat the observation record itself, including its interruptions and instrumental history, as an object of scientific investigation.

International collaboration was essential to that advance, and Czech participation went considerably beyond supplying raw measurements. The Pecný group became an analysis contributor to EUREF and later to the International GNSS Service, producing coordinate solutions, precise orbital information and other derived products. From 2002 it operated a EUREF local data centre, while an NTRIP broadcaster introduced from 2003 supported real-time distribution of observations. Such activities placed a continuing obligation on the group to maintain standards and meet demanding schedules. They were scientifically consequential because frequent combination with independent solutions exposed errors that might have remained invisible within a national network. A Czech result could be compared with analyses from other countries, and methods developed at Pecný could influence products used outside the Czech Republic. International reference systems thus became both a research subject and an instrument for assessing the quality of national scientific work.

The work of Jan Douša exemplifies the shift from collecting satellite observations to designing reproducible, time-sensitive analysis services. At the Pecný observatory he built sustained expertise in precise GNSS processing and led work on the relationship between orbit determination, station coordinates and the atmosphere through which signals travel. His 2010 study of near-real-time GNSS analysis described outcomes of the Centre for Earth Dynamics Research, including improvements in predicted satellite orbits and the production of tropospheric information for weather services. The achievement was not that a receiver could report its approximate position. Rather, the researchers had to model the satellite clock and orbit, account for signal delays, assess errors and distribute a result while it was still useful. A published description of those procedures makes clear how a Czech analytical centre became part of an international operational scientific network.

Pavel Václavovic and Gabriel Györi contributed to a later generation of software development at Pecný, working with Douša on the G-Nut library and its applications. Their 2013 account documented an architecture designed to read varied satellite data, manage precise products and implement estimation algorithms for positioning and atmospheric parameters. The subsequent G-Nut/Anubis publication showed how quality control could be adapted to signals from several navigation constellations. This mattered as GPS ceased to be the sole practical foundation of satellite navigation. More satellites and frequencies promise redundancy and improved geometry, but also produce new combinations of biases, multipath effects and data-quality problems. Openly described software allowed other analysts to examine those problems against the assumptions embedded in their own processing. The contribution therefore combined computational engineering with a more general scientific commitment to transparent and repeatable measurement.

The wider significance of GNSS analysis appeared in meteorology. A satellite signal traverses an atmosphere whose water vapour delays its passage; for a surveyor this delay is a nuisance to be corrected, but for an atmospheric scientist it can be a useful observation. Douša, Václavovic and colleagues estimated zenith tropospheric delays from continuous GNSS records, compared them with numerical weather models and explored the use of rapid estimates in forecasting. Their 2014 study on real-time delays and the 2016 Central European benchmark campaign brought Czech geodesy into the testing of advanced tropospheric models. Work with Michal Kačmařík, Radmila Brožková and international collaborators showed the practical necessity of independent observations, consistent processing and careful validation. This was a distinctive achievement: a research instrument designed to measure the solid Earth's reference geometry also supplied information about a changing component of the atmosphere.

The research on atmospheric delays also changed the institutional geography of scientific cooperation. Pecný joined European projects concerned with GNSS water vapour, severe weather and the interoperability of analytical services, including E-GVAP and GNSS4SWEC. These programmes brought geodesists into direct contact with meteorologists, numerical modellers and scientists analysing long records of humidity. Differences between a station's location, a model grid and the atmosphere actually sampled by a signal became questions to be investigated rather than ignored. The work of Georgi Guerova and a broad group including Douša helped synthesise the European state of GNSS meteorology in 2016. Such publications did not attribute every development to a single country; instead they demonstrated that Czech institutions had become participants in a collective methodological advance. The enduring value was an ability to contribute validated observations and expertise to a European measurement system with uses well outside geodesy.

A second line of internationally significant work involved the Doppler Orbitography and Radiopositioning Integrated by Satellite system, or DORIS. Unlike GNSS, DORIS uses a different configuration of satellite-based tracking and ground transmitters, providing an independent contribution to the realisation of terrestrial reference frames and the determination of satellite orbits. At Pecný, Petr Štěpánek and Vratislav Filler, with Urs Hugentobler and Douša, developed and assessed a processing route that brought DORIS observations into an analytical environment related to established GNSS software. Their 2010 paper traced the passage from experimental processing to an operational analysis centre. The importance of adding a second technique lay in the opportunity to compare results based on different instruments and error sources. An accurate global frame cannot be trusted merely because a single method has been processed with sophisticated software; independent techniques help expose systematic differences that would otherwise persist.

By the early 2020s the Pecný DORIS analysis centre was contributing to the International DORIS Service and the combination supporting ITRF2020. Refinements in orbit modelling, preprocessing and the treatment of satellite-specific disturbances improved the consistency of its estimates. This line of research demonstrates an often overlooked kind of achievement: mathematical and computational corrections may be modest when considered separately, yet their accumulation determines whether a network of observing systems can detect small

changes in the Earth's geometry. For a national research institute, participation also required long-term commitments to data processing, maintenance and international evaluation. Such commitments are less visible than a new instrument or a single prominent paper, but they support the stability of global scientific reference frames. Czech expertise in DORIS helped extend the country's geodetic work from regional positioning to the combination of techniques on a planetary scale.

National reference systems offered another measure of achievement. The Czech Republic inherited the S-JTSK plane-coordinate system and the Baltic height system after adjustment, both embedded in surveying practice and large quantities of existing maps and records. The introduction of GNSS did not erase these conventions. Instead, geodesists had to reconcile observations expressed in international terrestrial systems with coordinates recognised by national authorities. The Czech Office for Surveying, Mapping and Cadastre worked with research institutions on successive improvements to the implementation of ETRS89, including the new Czech realisation introduced in January 2011. The scientific problem was not one of replacing an old number with a modern number. It was to account for distortion, transformation uncertainty, differing epochs and the fact that points may move. The resulting procedures allowed observations from new instruments to be connected with records compiled over several generations without pretending that their reference conditions were identical.

The growth of CZEPOS illustrates how this research entered a widely used national service. The permanent GNSS station network, developed from 2004 onwards by the surveying administration, provided observations and correction products for accurate positioning. It supported a range of activities from cadastral surveys and construction to engineering investigations and environmental measurement. Its significance to geodesy is better described as infrastructure than as a single scientific discovery. Stations had to be installed on stable sites, their coordinates determined, hardware changes documented and service performance monitored. Users also required clearly defined transformations from international geocentric coordinates into national spatial systems. Pecný's participation in monitoring the service showed the value of keeping scientific analysis connected with routine provision. This combination of an operational network and an independent analytical tradition enabled Czech geodesists to test instrument performance and reference consistency under conditions encountered by working surveyors.

Height determination made the link between everyday measurement and fundamental geodesy especially clear. Satellite instruments directly provide a height above a reference ellipsoid, whereas engineers and mapmakers ordinarily need a height connected with the Earth's gravity field. Bridging these quantities requires a model of the quasigeoid or a related physical surface, supported by ground gravity and levelling. Jan Kostelecký, Jakub Kostelecký, Ivan Pešek, Jaroslav Šimek, Otakar Švábenský, Jiří Weigel and Antonín Zeman contributed to the comparative study of Czech quasigeoid models. Their 2004 publication in Studia Geophysica et Geodaetica documented work that joined gravity information with satellite positioning and levelling. The subsequent CR-2005 model refined the national surface using a much denser set of control points. Its practical value was that different methods of measuring

height could be related through a documented model whose accuracy could be investigated rather than presumed.

These quasigeoid studies also reveal why Czech physical geodesy required cooperation across institutions. A mathematical model can incorporate gravity anomalies, terrain information and long-wavelength fields derived from global satellites, but it cannot compensate for faulty ground measurements by calculation alone. Conversely, well-observed benchmarks do not by themselves determine a continuous reference surface over the whole country. Contributors from the research institute, technical universities and national surveying services brought together different types of evidence. Comparisons between modelled and measured heights exposed regional discrepancies and helped identify where new observations were needed. Over time, improved global geopotential models and more extensive GNSS measurements enabled researchers to revisit earlier national solutions. A major result of the period was therefore the maintenance of a cycle of model construction, independent validation and revision, rather than a claim that one model had permanently solved the height problem.

Petr Holota represented an important line of mathematical physical geodesy, centred on the theory of gravitational potential and the boundary-value problems that underlie gravity-field determination. This work differs from a regional measurement campaign in its scale of abstraction, but it is no less dependent on actual observational questions. Recovering a gravity field from observations made at the surface or from moving satellites requires assumptions about the domain, boundary conditions and the behaviour of the field. The theoretical choices affect how errors and incomplete coverage propagate into the result. Holota's position within the Pecný research environment helped preserve a tradition in which derivations were not treated as detached formal exercises. They could inform the interpretation of new measurement techniques while also exposing the limitations of simplified models. Such work sustained the intellectual depth of Czech geodesy during a period when rapid technological change might otherwise have encouraged a purely instrumental view of progress.

Pavel Novák developed a related research programme on regional gravity fields, terrain corrections and the mathematical treatment of geodetic observations. His publications ranged from calculations using dense local gravity and elevation data to analyses of satellite-derived information. A 2010 review of high-resolution components of the Earth's gravitational field provided an especially useful synthesis of how small-scale terrain-related effects could be understood within broader gravitational models. The contribution was methodological as much as regional. The gravitational signal recorded by a sensor reflects masses at different distances and spatial scales, so a fine grid of observations does not automatically isolate a local geological structure. Terrain, atmospheric masses and global field components must be modelled consistently. Novák's work helped show why model resolution, numerical method and the physical meaning of the estimated quantities must be considered together when gravity information is converted into a map.

Czech researchers also used dedicated satellite missions to test gravity-field theory. The missions CHAMP, GRACE and GOCE supplied information that traditional ground surveys could not collect with the same global coverage. Jaroslav Klokočník, Jan Kostelecký, Aleš Bezděk, Novák and collaborators examined how orbital geometry, observation characteristics

and numerical representation shaped the recovered field. Their analyses of satellite-track variability and gravitational signatures extended Czech participation into an international field that linked geodesy, orbital mechanics and geophysics. One achievement was to make the limitations of satellite products more visible. Two models may differ because of sampling, truncation or the treatment of disturbing forces rather than because the Earth's gravity changed. Comparative work of this kind gave geodesists a disciplined way to use attractive global datasets while resisting the temptation to regard every small feature of a colour-shaded map as independently established physical evidence.

Klokočník's research demonstrates the breadth of application possible when gravity and satellite dynamics are treated jointly. With Kostelecký and Bezděk, he used modern gravity models to investigate the signatures of geological structures, and the collaboration eventually produced a Gravitational Atlas of Antarctica in 2017. The atlas assembled gravitational evidence for a continent where direct observation is difficult and unevenly distributed. In 2022, the wider team including Václav Cílek and Gunther Kletetschka published an atlas of the Moon's gravity and magnetic fields. The geographical scale had changed from Czech territory to polar and extraterrestrial environments, but the methodological concern remained recognisable: how to interpret physical fields observed indirectly, and how to keep inference distinct from measurement. These works showed that researchers associated with Czech geodesy could contribute to questions in planetary science without abandoning the mathematical and observational foundations of their original discipline.

Absolute gravimetry formed a more local, yet equally demanding, research tradition. The Pecný observatory began repeated absolute gravity measurements in 2001, using instruments that estimate gravitational acceleration from the precisely observed motion of a test mass. Unlike relative surveys, which determine differences between sites, such measurements establish values that can be traced to a metrological standard. Jakub Kostelecký and Vojtěch Pálinkáš played important roles in this work, alongside Jaroslav Šimek, Miloš Vaľko and other colleagues. A gravimeter's result depends on stable time and length references, the behaviour of the instrument, local environmental conditions and corrections for known periodic effects. Making gravity observations comparable across years therefore requires much more than placing an instrument on the same point. The central achievement was the establishment of a long-term programme in which repeatability and uncertainty could be examined explicitly.

Pálinkáš became a leading figure in the scientific and metrological development of Czech absolute-gravity measurement. His studies with colleagues considered repeated determinations in the Czech Republic and neighbouring countries, including the effects of hydrological variability and changes between instruments. A 2013 paper in Journal of Geodesy compared observations conducted during 1991–2010 and showed the need to account carefully for circumstances that can mimic long-term geophysical trends. The research group also participated in international comparisons of absolute gravimeters, allowing the national scale of gravity acceleration to be checked against independent instruments. The Czech national standard, maintained at VÚGTK under the metrology system, gave this activity a formal basis. Its scientific meaning lay in the ability to demonstrate that a small reported difference

between places or dates was larger than the uncertainty attributable to the apparatus and measurement procedure.

From 2007, continuous records from a superconducting gravimeter at Pecný added a further dimension. Such an instrument is particularly sensitive to variations in gravity over time and is therefore complementary to repeated absolute measurements. The record can be used to study tides, atmospheric and hydrological effects and other processes that influence the local gravity field. In work associated with the International Geodynamics and Earth Tide Service, Pálinkáš, Kostelecký and Vaľko helped make Pecný measurements available within international scientific data systems. One methodological strength was the opportunity to connect absolute values recorded on selected dates with a continuous time series between them. Investigators could examine whether an apparent secular change was influenced by seasonal water storage or other transient signals. The use of two different instrumental principles provided a check that neither method could offer on its own.

Gravity measurements at Pecný consequently became a bridge between national metrology and research into the dynamics of the Earth system. Repeated observations across a network of absolute stations can identify places where local processes or instrumental uncertainty warrant further investigation. Continuous gravimetry can reveal fluctuations that would be missed by occasional field campaigns, although interpreting them requires models of tides, atmospheric loading and hydrology. Czech work in this domain illustrates a form of scientific achievement that is rarely captured by the number of new stations alone. A station must be characterised, reference values maintained, different generations of instruments compared and data supplied in forms suitable for independent analysis. In the 2020s the programme extended attention to seasonal gravity changes across Czech stations, showing that long-established metrological infrastructure could still generate new research questions about environmental mass redistribution.

Geodynamics supplied another arena in which the value of continuous observation became evident. The Bohemian Massif and adjacent mountain belts are often described as comparatively stable, but stability at one scale does not rule out measurable local deformation or the slow adjustment of faults and rock masses. Researchers at the Institute of Rock Structure and Mechanics of the Czech Academy of Sciences developed permanent and campaign-based geodetic networks to investigate such movements. Vladimír Schenk and Zdeňka Schenková were prominent in building this approach, which treated the distribution of observing points as part of the scientific problem. Stations placed on different structural blocks may detect relative displacements, while a station influenced by local instability may obscure a regional trend. Their work placed geological interpretation, GNSS processing and careful site selection within a single framework for studying the contemporary behaviour of the crust.

The GEONAS network became a documented outcome of these efforts. In 2010, Schenk, Schenková, Milada Cajthamlová and Zdeněk Fučík described its development as a set of permanent GNSS stations located with attention to tectonic structures of the Czech Republic. The authors were explicit about the need to improve the spatial distribution of stations and to manage the quality of their records. Research on the Sudetes, including a further 2010 study by Schenk and colleagues with Jan Bosy and Bernard Kontny, tested whether apparent

displacement signals were dependable enough for geodynamic interpretation. These publications were consequential because they challenged a convenient but unreliable assumption that the numerical output of a positioning programme is equivalent to movement of the ground. A geodetic time series acquires geological significance only after reference stability, local effects and the statistical behaviour of observations have been considered.

The Western Bohemian earthquake region raised related questions at smaller spatial and temporal scales. Episodes of earthquake swarms near the Nový Kostel area motivated joint investigation by geophysicists and geodesists into possible relations between seismic activity, fault processes and surface displacement. Work by the Institute of Geophysics of the Academy of Sciences and cooperating institutions combined seismic observations with geodynamic measurement, including the WEBGEODYN network. Geodetic signals in such settings are not straightforward, since a position measured after a swarm need not differ detectably from the one measured before it. The research therefore emphasised repeated measurement, reliable reference stations and interpretation alongside independent geophysical evidence. Its achievement was not the discovery of a simple formula linking every earthquake to an observed surface shift, but the creation of a multi-method framework in which such a hypothesis could be tested and sometimes rejected.

Other Czech researchers investigated movement in the Sudetes, the Boskovice Furrow and comparable fault-related environments. Work associated with Jiří Weigel, Otakar Švábenský, Ladislav Pospíšil and their collaborators integrated geodetic measurements with knowledge of geological structures and older geophysical surveys. A 2017 investigation of the northern Boskovice Furrow, e.g., used geodetic and geophysical evidence to consider areas of potential geodynamic risk. Studies in the Sudetes drew attention to how the geographical distribution of observations influences estimates of movement across tectonic zones. A regional displacement field may appear convincing on a map even when observations are too sparse to resolve the variation at a fault. These studies contributed a valuable sense of scale and caution to Czech geodynamics, connecting the numerical precision of instruments with the geological credibility of the resulting spatial interpretation.

The institutional consolidation of observational geoscience made such caution easier to practise. CzechGeo, linked to the European Plate Observing System, brought together permanent geophysical observatories and networks, including seismic, geomagnetic, gravimetric and GNSS components. The participating organisations included the Institute of Geophysics, the Institute of Rock Structure and Mechanics, the Institute of Geonics, the Institute of Physics of the Earth at Masaryk University, Charles University, VÚGTK and the Czech Geological Survey. The value of this arrangement went beyond a catalogue of stations. It improved the prospect of locating, comparing and reusing observations collected for different purposes, and encouraged a shared account of metadata and quality. For geodesists, access to seismic timing, geological context and independent gravimetric information helped prevent a displacement signal from being interpreted in isolation. The consortium thus represented a research achievement grounded in scientific coordination as well as measurement.

The Institute of Geonics of the Academy of Sciences and VŠB–Technical University of Ostrava developed a complementary concentration of applied geodetic expertise around mining and industrial landscapes. Long periods of extraction altered stresses and sometimes produced surface subsidence, making reliable estimates of vertical and horizontal movement important for the interpretation of environmental and engineering risk. University research in mine surveying, precise engineering measurement and geodetic monitoring was increasingly combined with satellite radar interferometry and modern spatial data. The scientific question was how to distinguish movement caused by active or historic extraction from atmospheric artefacts, processing errors and broader regional deformation. This setting gave Czech research an unusually demanding field laboratory. It also made clear that a technique validated on a rigid benchmark cannot necessarily be transferred without adjustment to terrain affected by rapid or uneven subsidence.

Michal Lazecký and Eva Jiránková made substantial contributions to the development of satellite interferometric approaches in the Ostrava–Karviná coalfield. Their 2013 work addressed the optimisation of InSAR monitoring around the Lazy mining plant, where the signal could be distorted by rapid movement and changes in surface coherence. The eventual expansion of Sentinel-1 observations created opportunities for more regular mapping over much larger areas. A 2020 paper by Lazecký and colleagues presented the IT4S1 system for automated displacement monitoring across Czechia. Such work illustrates a wider development in geodetic science: an increasing ability to observe spatially distributed movement rather than only the behaviour of a limited number of benchmarks. Yet the authors' attention to processing and validation also showed that interferometric displacement is measured along a satellite's viewing direction and must not be equated uncritically with a full 3D movement vector.

Engineering geodesy supplied another research tradition in which the limits of measurement could have immediate consequences. At the Czech Technical University in Prague, investigators studied the behaviour of structures and the design of precise observing networks, while the practical problems of deformation monitoring encouraged new combinations of total stations, levelling, GNSS and laser measurement. The Prague Castle area provided an instructive case: a 2010 study by Jiří Procházka, Jan Záleský, Tomáš Jiřikovský and Jaroslav Salák documented methods of long-term stability monitoring in a complex historic environment. Changes in the position of a point might reflect an actual structural process, but could also originate in observation geometry, reference choice or seasonal changes. Research achievements in this field consequently rested upon establishing controls and consistent observation histories as well as collecting large quantities of measurements. The cultural significance of a historic site did not alter the need for rigorous geodetic inference.

The Czech Technical University also sustained a mathematical and computational school of geodetic adjustment. Aleš Čepek's 2002 paper on the GNU GaMa project introduced open software for the adjustment of geodetic networks, with observation data represented in a structured form. His subsequent work with Jiří Pytel examined numerical procedures for least-squares estimation, including methods appropriate to singular systems and free networks. This contribution addressed a problem fundamental to all precise measurement: observations

do not independently determine every coordinate without suitable reference constraints. Open implementations made the numerical choices easier to inspect and offered teaching and research benefits well beyond a single surveying project. They also strengthened the link between mathematics, programming and the practical adjustment of geodetic observations. The achievement was not chiefly a commercial application; it was a documented, accessible way of testing the computational reasoning on which geodetic conclusions depend.

The Faculty of Civil Engineering at the Czech Technical University combined this theoretical inheritance with broader training in geomatics. Its Department of Geomatics developed work in satellite positioning, surveying, geospatial data, laser scanning and photogrammetry while maintaining the foundations of physical and mathematical geodesy. Karel Pavelka became particularly associated with photogrammetry and the spatial documentation of cultural heritage. His teaching publications and research programme connected digital image measurement with terrestrial surveying, laser scanning and the recording of architecturally complex objects. This direction falls at the boundary between geodesy and cartography, but it remains pertinent to the achievement of the former: faithful 3D documentation requires reliable scales, control points, coordinate transformations and uncertainty assessment. The continuity of university teaching ensured that successive generations of Czech specialists could understand these foundations even as the instruments and their digital outputs changed.

Brno University of Technology formed another important site of technical-geodetic training and investigation. Its geodetic research tradition brought together satellite positioning, coordinate systems, engineering measurements and the practical study of ground movement, contributing to professional expertise in Moravia and beyond. The involvement of researchers such as Otakar Švábenský and Jiří Weigel in national quasigeoid and regional geodynamic publications demonstrates the connections between university departments and other scientific organisations. Their work could begin with a regional measurement problem yet produce evidence relevant to a larger physical model or national reference framework. Such cooperation is particularly significant in a field where expensive instruments and sparse reference stations make isolated institutional programmes inefficient. Rather than competing for wholly separate datasets, the more productive Czech research networks often depended upon shared benchmarks, comparable processing and joint interpretation of results.

The University of West Bohemia in Plzeň developed a research and teaching profile concerned with geomatics, spatial information and methods of geodetic measurement. Its contribution was especially valuable in translating the theoretical basis of geodesy into computational approaches to spatial data and practical analysis. The distinction between surveying and geoinformatics became less rigid as coordinates increasingly entered databases and digital models rather than remaining confined to paper plans. Still, the scientific challenges did not disappear into software. Decisions about reference frames, precision, measurement geometry and data lineage determine whether independent datasets can be combined meaningfully. By engaging with modern geomatics, Czech university programmes helped preserve these questions within the education of specialists likely to work across government, engineering

and academic institutions. This educational and methodological role deserves recognition alongside more easily counted publications and equipment acquisitions.

The results of university and institute research circulated through international geodetic journals as well as specialised Czech publications. Studia Geophysica et Geodaetica connected the mathematical and physical branches of the field with geophysics, while Acta Geodynamica et Geomaterialia offered a venue for studies of deformation, GNSS networks and gravity. Acta Polytechnica published work on geodetic computation and the technologies of surveying. The international journals Journal of Geodesy, GPS Solutions, Advances in Space Research, Remote Sensing and Atmospheric Measurement Techniques supplied additional readerships. Their disciplinary differences are instructive: an algorithm for satellite orbits, a gravimetric reference comparison and a study of tropospheric water vapour may employ related observations but are judged by different questions. Czech researchers showed their international engagement by placing results into these varied conversations and by revising methods in response to their demands.

The literature also records a substantial change in what counted as a convincing geodetic result. During the early 1990s, a new observation series or the establishment of a reference station could be an achievement in itself, especially when access to international measurement systems was being rebuilt. In subsequent decades, the research questions increasingly concerned the stability of the series, the compatibility of independent techniques and the ability to reprocess older observations with improved models. Publications on the EUREF network and on the Pecný analysis services demonstrated how methodological choices could change a coordinate or delay estimate without any corresponding physical event. Works on gravimetry and geodynamics posed the same question in a different setting: how can a researcher tell that a measured difference belongs to the Earth rather than the instrument? Across the field, advances in data availability made stringent tests more feasible, while also revealing problems earlier observations were too sparse to expose.

The chronology of landmark publications reflects these changing standards. The 2002 study of GNU GaMa showed a commitment to transparent computational methods; the 2004 quasigeoid paper made the integration of Czech gravity and height observations a subject of systematic comparison. During 2010, papers on near-real-time GNSS processing, DORIS analysis, GEONAS, gravity measurement and satellite models appeared in Acta Geodynamica et Geomaterialia, giving a particularly concentrated account of the country’s research capabilities. The 2013 G-Nut library paper and subsequent Anubis work documented an expanding range of satellite signals and reproducible software solutions. Publications from 2014 to 2019 demonstrated the usefulness of tropospheric products for meteorology and precise positioning. The later work on automated deformation mapping and international reference-frame combinations carried the story into a period when the interpretation of large observation streams became as important as their acquisition.

It would be misleading to arrange these publications into a simple national ranking. Some were written primarily to solve a Czech technical problem, while others dealt with questions of international satellite measurement or the gravitational fields of distant environments. A paper could become important by introducing a theoretical method, by providing a well-

characterised dataset or by documenting an instrument sufficiently carefully for later results to be compared. Pecný's contributions to international services and theoretical monographs should be judged differently, although both depend upon traceability. The observations, assumptions and methods are described in terms that permit another researcher to test them. This has particular historical value in geodesy, where a reference system or an apparent ground movement can be reinterpreted when longer time series and better physical models become available.

International participation nevertheless brought demands that were not always easy for a small research community to sustain. Reference-frame solutions, orbit products and meteorological parameters often have to be delivered regularly, with continuity across staff changes and instrument replacements. The Czech research system met these requirements through cooperation between publicly maintained infrastructure, specialised research groups and universities training new experts. Research connected with national geodetic foundations gained credibility through international comparison, while external collaborations gained access to a well-documented Central European observing region. The most useful measure of the resulting integration is not the number of organisational memberships but the persistent contribution of data, algorithms, reference values and critical assessments. This form of collaboration made the Czech observatories and analytical centres relevant even when the scientific question concerned global satellite geometry rather than the national territory alone.

By 2025, Czech geodesy had acquired a recognisable profile built upon several mutually reinforcing accomplishments: reliable participation in international satellite reference systems, models connecting gravity and height, long-term absolute and continuous gravimetry, research networks for monitoring deformation, and adaptable methods of numerical analysis. Institutions in Prague, Zdiby, Pecný, Brno, Ostrava and Plzeň contributed different expertise, while collaborations with the Academy of Sciences and European scientific services allowed that expertise to be combined. The leading researchers did not form a single unified school with one theory or instrument; their shared achievement was to preserve the measurability of change as a rigorous scientific question. The resulting legacy extends beyond geodesy itself. Precise positions support physical geography and engineering, gravity records inform geophysics, deformation measurements clarify environmental risks, and atmospheric estimates contribute to meteorology. What connects these uses is the discipline's insistence that observations remain comparable, explainable and open to revision.

Part Twelve

Cartography, Geoinformatics and Spatial Observation Technologies

Cartography after 1993: From Printed Maps and National Atlases to Digital and Interactive Representation

The modern history of Czech cartography cannot be described simply as a passage from paper to screens. In 1993, when the independent Czech Republic inherited the maps, technical standards and professional institutions of Czechoslovakia, a printed sheet remained a dependable means of recording terrain and communicating geographical knowledge. Yet the conditions under which that sheet was made, revised and consulted were beginning to change. Digital records promised a different relationship between observation and representation: a road could be updated in a database before it was drawn on a new sheet, and the same geometry could support several maps intended for different readers. Over the following three decades, Czech cartographers tested how far this possibility could be realised in a country with a dense settlement network, carefully documented land ownership, complex topography and a long tradition of thematic atlases. Their achievement was not the abandonment of established map principles but the construction of ways to apply them to changing spatial information. The resulting history combines state survey work, academic inquiry, specialised publishing and a gradual expansion of public access to geographical evidence.

At the beginning of the period, the professional inheritance was substantial. State topographic series covered the country at several scales, cadastral maps described property boundaries, and universities taught the projections, signs, lettering and generalisation needed for precise representation. Earlier Czech and Czechoslovak cartographers had developed practices for documenting a landscape in which landforms, administrative divisions and settlement patterns demanded different treatment. Those practices were valuable, but their institutional environment had changed. The new state needed reliable maps for its own administrative structure and for a property market undergoing transformation. Survey offices also had to serve ministries, local authorities and commercial users whose demands were no longer organised within a single planning system. At the same time, geographical research had greater freedom to compare techniques and exchange data internationally. The first task was therefore one of continuity under new conditions: retaining accumulated cartographic knowledge while redefining who maintained the underlying information, how revisions were financed and what kinds of map could be distributed.

The Czech Office for Surveying, Mapping and Cadastre, usually identified by the abbreviation ČÚZK, occupied a central position in that transition. Created within the institutional arrangements of the new republic, it supervised a field in which an official map had both a scientific and an administrative character. A line on a topographic sheet might be a simplified

representation of a physical object, whereas a line on a cadastral map could have direct implications for identifying a parcel of land. These were not interchangeable descriptions, even when both were displayed on the same screen. The Land Survey Office and cadastral authorities maintained different strands of the information from which maps were produced. Their work illustrates an enduring feature of national cartography: a map's reliability depends on organised observation, maintenance and standards long before the visible image is prepared. Digital technology made the distinction more important, since readers might see precise-looking boundaries and topographic features together without recognising that they had been created for different purposes and with different degrees of authority.

The establishment of the Fundamental Base of Geographic Data of the Czech Republic, known as ZABAGED, changed the practical foundations of national topographic mapping. Its initial construction began in 1995 through the vector digitisation of the printing materials for the basic 1:10,000 map. Much of that conversion was finished by 2001, although built-up areas and attributes required further work. By 2004, the addition of settlement features and the connection of individual mapping units had produced a more continuous geographical database. The importance of this chronology lies in the sequence of work rather than in the mere adoption of computers. Scanning a sheet yields an image of its content; representing roads, watercourses and buildings as separate objects creates data that can be updated, queried and combined. Czech practice moved progressively from the former towards the latter, while retaining the responsibility to decide how those objects should appear at different scales. This provided a common source for official maps and a foundation for many other geographic applications.

A seamless digital dataset did not remove the cartographer's judgment. The original map sheets had been designed around the limitations and advantages of particular scales, and their content reflected decades of decisions about which objects deserved to be visible. In a digital database, a feature may exist regardless of whether its symbol can be legibly drawn at 1:10,000 or 1:100,000. A narrower road, e.g., may need to be displaced so that it does not disappear beneath a railway, while a small building may be omitted from a regional overview even when its position is known. In the Czech case, the growing use of ZABAGED made such questions part of a reproducible production chain. Cartographic generalisation became a controlled transformation of spatial objects, not merely a final adjustment of artwork. This required consistency between data models and graphic specifications, and it revealed why technically accurate coordinates do not automatically yield a usable map. A readable representation still depends on hierarchy, contrast, selection and a defensible account of the intended reader.

Topographic mapping also had to accommodate the country's changing administrative geography. The introduction of fourteen self-governing regions at the turn of the millennium and the changing allocation of administrative functions affected the spatial references needed by public authorities. Regional atlases, planning maps and national overviews required boundaries that matched the institutions being described. The new regions did not create new mountains or rivers, but they altered the geography of public services, statistical aggregation and political representation. This gave thematic cartographers an immediate problem: a shift in administrative units can make one map seem to contradict an older one even when the

underlying population or economy changes little. Czech cartographic work increasingly distinguished the geometry of administrative boundaries from the data collected within them and the decisions made about aggregation. This distinction became important in later atlases of social and economic transformation, where the scale of observation could decisively influence the patterns visible to readers.

The geographical names carried by official maps formed another specialised layer of national knowledge. In 1997, work began on digitising standardised names for the Geonames database, drawing on records assembled under the national geographical naming system. Coverage was completed for the entire country in 2005, with successive territorial revisions thereafter. This was more than the computerisation of labels. A name links a geographical object to language, local usage, public administration and historical memory; a mistaken or inconsistent form can compromise searching and communication even when the object's coordinates are correct. The database made it possible to maintain names as information associated with features rather than as text permanently embedded in a printed image. Cooperation with municipalities and cadastral offices helped reconcile standard forms with local evidence. For cartography, Geonames supplied a means of making naming decisions visible across map series and digital services, while also retaining the need for contextual judgement when historical and contemporary names differed.

The development of orthophotography provided a different route from an observed landscape to a map-like image. Black-and-white orthophoto coverage from 1998–2001 was followed by experimental colour coverage in 2002 and a regular colour programme beginning in 2003. The programme initially covered about one third of the national territory annually; from 2012, its cycle covered roughly half. Improvements in photography and processing progressively reduced the ground pixel size, reaching 0.125 metres from 2021. These changes altered what could be checked visually: additions to a settlement, new roads, forest clearings and some patterns of land use became easier to recognise and compare through time. An orthophoto, however, does not classify every object or explain its function. Its colours and textures may support verification of a database or a planning decision, but the interpretation still requires other observations. Czech map production benefited from the growing ability to place a current photographic image beside selected cartographic symbols without confusing the two forms of evidence.

Digital terrain representation made another formerly labour-intensive operation more adaptable. Contours and spot heights had long been central to Czech topographic mapping, particularly in mountain regions where relief governs the location of settlements and communications. As elevation information became available in computer-readable form, a cartographer could derive hillshading, slope classes, profiles and alternative depictions for a chosen purpose. The same dataset might support a conventional contour map, an analytical image of terrain exposure or the base of a 3D scene. Such flexibility also made mistakes easier to multiply: an unsuitable interpolation procedure could create convincing but fictitious details, while excessive shading could make thematic colours difficult to distinguish. Academic work on digital terrain models therefore had significance beyond software training.

It gave Czech cartographers a framework for examining how the resolution and construction of a surface condition the reliability of the landscape that appears on the page or screen.

The 1990s expansion of geographical information systems encouraged universities to revisit the relationship between cartography and geographical analysis. Vít Voženílek, working at Palacký University in Olomouc, was among those who placed digital spatial data, terrain modelling and geographic visualisation within a coherent programme of teaching and research. His publications of the early post-independence period addressed the conversion of data and the possibilities of digital cartography rather than treating computers as faster drawing instruments. A 1993 paper on digitisation and data conversion, together with subsequent work on terrain modelling, reflects how urgently researchers needed to explain the difference between storing a map image and structuring geographic information. The intellectual problem was also pedagogical. Students trained in symbol design needed to understand databases, while those acquiring technical GIS skills needed to learn why visual representation could mislead. Olomouc's contribution lay in making these subjects mutually informative at a time when the profession's practical tools were rapidly changing.

Other academic centres approached the transition from different directions. At the Czech Technical University in Prague, cartographic work was embedded in geomatics and surveying, where positional accuracy, reference systems and the production of topographic or historical maps remained important. Charles University connected map-making with human, physical and historical geography, allowing thematic representation to develop alongside the questions asked by geographers. Masaryk University in Brno sustained an interest in regional and environmental mapping, and Ostrava provided expertise in thematic methods and geographical information. Each setting encouraged particular research habits rather than constituting a sealed school. A project concerned with regional inequality required careful statistical classification, while one dealing with old city plans demanded attention to changing street layouts, projections and the provenance of archival sources. The diversity of institutions helped Czech cartography develop as both an independent craft of representation and a method serving disciplines that asked very different questions of space.

The continued publication of printed atlases during the digital transition shows why the change of medium should not be mistaken for a simple succession of technologies. An atlas gives its audience an organised argument about territory through an ordered sequence of maps, texts and comparisons. It allows a phenomenon described on one page to be interpreted against the physical or historical conditions shown elsewhere. Such sequencing remains difficult to reproduce through a collection of unrelated web layers. Czech atlas makers retained the printed format for major syntheses while increasingly using digital geographic data to prepare the individual maps. This combination was especially productive in scientific fields whose results were dispersed across specialised observations and databases. Researchers could assemble information collected by different institutions into a consistent cartographic vocabulary, then use the design of the atlas to distinguish established knowledge from estimates or interpretations. The atlas consequently remained a scholarly publication rather than merely a store of pictures, and its production offered a demanding test of interdisciplinary cooperation.

The Climate Atlas of Czechia, published in 2007 by the Czech Hydrometeorological Institute and Palacký University, was a prominent example. Prepared under the leadership associated with Radim Tolasz and colleagues, with substantial cartographic participation by Vít Voženílek, it brought together modern climatic observations and a systematic approach to presenting their regional variation. The project addressed a clear historical limitation: the widely used Czechoslovak climate atlas of 1958 rested on an observation period that could no longer adequately characterise recent conditions. The new atlas offered a coordinated set of maps for temperatures, precipitation and other climatic characteristics, accompanied by methodological explanation. Its significance was not restricted to the subject of climatology. It demonstrated that computer-assisted cartography could serve a major national synthesis without sacrificing control over classes, legends, colour schemes or the relationships between maps. It also established a resource through which scientists and other readers could compare the country's climate at a regional scale rather than relying on isolated station records.

Climate mapping exposed a methodological difficulty that became familiar across Czech thematic cartography. Measurements from stations have definite locations, while a climatic field is represented as though it extends continuously over an area. The map maker must therefore decide how elevation, terrain, station density and interpolation affect the surface that readers see. A smoothly coloured map may appear more certain than the available observations justify. In mountainous Czech border areas, where climate varies sharply over short distances, such decisions are particularly consequential. The 2007 atlas required the scientific findings of climatologists to be translated into a consistent visual language. It also showed that a map of average conditions differs conceptually from a map of an individual event, even when their colours look similar. Cartographic design could help readers keep that distinction in view through clear legends, explanatory text and appropriate map scales. These considerations became increasingly important as digital interfaces made it easy to place several meteorological products beside one another.

The Landscape Atlas of the Czech Republic, issued in 2009, represented an even broader attempt to make the country comprehensible through maps. Edited by Tatiana Hrnčiarová and prepared under the auspices of the Ministry of the Environment and the Silva Tarouca Research Institute for Landscape and Ornamental Gardening, the volume extended across 331 pages and contained more than a thousand maps. Its subject, landscape, required the integration of relief, ecosystems, land use, settlement, cultural heritage and human influence rather than the description of a single environmental variable. The atlas therefore provided an arena in which cartographic techniques were used to relate different kinds of scientific evidence. It was also a national project produced in the era of geographical databases: its printed pages depended on digital techniques of compilation, analysis and graphic preparation. The resulting work illustrated how a major atlas could bring the history of a landscape into dialogue with its contemporary environmental condition without reducing either dimension to an ornamental background.

In the Landscape Atlas, choices about scale and synthesis had special interpretative weight. The detail available for a forest stand or a village differs from the information suitable for a

nationwide map of landscape types. Cartographers had to translate field knowledge into boundaries and categories that would remain legible at the atlas scale, often revealing transitional areas rather than sharp divisions. A landscape unit may be scientifically useful even though its limits cannot be surveyed like those of a cadastral parcel. Making that distinction visible is part of the ethics of environmental cartography: a carefully drawn border must not suggest a certainty that the classification lacks. The atlas offered a broad overview while preserving examples of more specific landscapes and regional processes. Its maps were consequently capable of supporting environmental education and planning as well as scholarship. The volume stands as evidence that national cartography could integrate heterogeneous research into a coordinated representation of a changing country.

A further example came from population and social geography. The Atlas of Socio-spatial Differentiation in the Czech Republic, edited by Martin Ouředníček, Jana Temelová and Lucie Pospíšilová in 2011, translated the consequences of the post-socialist transformation into a series of geographical comparisons. Its maps examined differences between municipalities in demographic characteristics, housing, commuting and social conditions. Instead of accepting a single national average, the authors made territorial variation central to the explanation of social change. The cartographic achievement depended on the careful handling of statistical units and on connecting a map with concise interpretation. A municipal indicator can reveal a regional contrast while concealing variation between neighbourhoods; a striking colour may draw attention to a small settlement whose significance is quite different from that of a metropolitan district. By drawing on both geographical analysis and thematic design, the atlas offered an example of maps used as research arguments. It also exemplified the growing role of university teams as publishers of national cartographic syntheses.

The comparison of social maps also raised questions about visual responsibility. Maps of unemployment, migration or welfare provision can easily create the impression that certain places have an inherent character. In reality, the mapped value may reflect age structure, local institutional arrangements, the number of inhabitants or the geographical scale at which statistics are available. Czech social cartographers increasingly addressed these limitations through accompanying texts, carefully selected indicators and explicit geographical units. The 2011 atlas illustrated how related maps could help readers test interpretations instead of attaching a permanent label to a municipality. A pattern of suburban housebuilding, e.g., becomes more informative when read alongside maps of age composition, mobility and service provision. Through such cross-reading, the atlas made visible the connections between changing settlement geography and social differentiation. Its value lay partly in resisting the reduction of a complex transformation to a single coloured surface.

Historical atlas cartography followed a parallel but distinct path. The Institute of History of the Czech Academy of Sciences maintained a collection of historical maps and a research tradition extending well before 1993. The Historical Atlas of Czech Towns series began publication in 1995, presenting individual settlements through historical plans, images, documentary reconstructions and interpretative texts. The series was shaped by the principles of European urban historical atlas work, which encouraged consistent forms of representation while allowing for each town’s particular history. Its objects were cities as changing spatial

systems rather than fixed points on a contemporary map. A plan made before an industrial expansion, for instance, could be compared with later street networks, property structures and building patterns. The atlas format thus connected archives, historical geography and cartographic reconstruction. These publications demonstrate how printed cartography remained intellectually active during the period of rapid digitalisation, especially where the object of study demanded a detailed account of change over several centuries.

Producing a historical map involves a different kind of uncertainty from compiling a contemporary topographic database. An archival plan may show an administrative intention rather than a completed street, and an old boundary may be described by a source whose geographical precision cannot be established. When a historical image is placed into a modern coordinate system, geometrical discrepancies become visible, but they do not necessarily prove that the original cartographer made a mistake. They may reflect an alternative survey technique, an altered landscape or a different reason for drawing the map. Czech historical cartographers, including researchers working with Eva Semotanová, developed approaches that treated source criticism as inseparable from graphical reconstruction. This allowed maps of earlier settlements and territories to be used in research without stripping them of their documentary context. Digital georeferencing widened the possibilities for comparison, but the interpretation still depended on the historian's judgment about the provenance and purpose of the source.

The Academic Atlas of Czech History, published in 2014 under the editorial leadership of Eva Semotanová and Jiří Cajthaml, brought historical scholarship and technical cartography together on an unusually ambitious scale. Prepared through cooperation between the Institute of History and the Czech Technical University in Prague, it presented Czech history through maps, cartographic models, illustrations and graphs, with a sustained interest in European connections. Its development took place after historians had gained wider opportunities to re-examine subjects and evidence that had previously been restricted or interpreted within narrower institutional frameworks. Cartography supplied a means of placing developments in time and space, while the atlas structure required the authors to agree how heterogeneous findings should be represented consistently. The book was recognised beyond specialist circles, including an award in the 2015 Magnesia Litera competition. This recognition was significant for the public standing of historical cartography: a rigorously prepared atlas could contribute to national historical understanding without being confined to a technical readership.

The academic historical atlas also highlighted the need to distinguish temporal evidence from the appearance of temporal certainty. Political boundaries, population distributions and military operations rarely change in perfectly regular steps, yet an atlas conventionally presents them on pages bearing particular dates. The choice of that date may correspond to an event, a source or a convenient analytical interval. A historical map must signal which of those meanings is intended, especially when readers compare several periods. In the Czech lands, successive state formations and administrative reforms make this problem especially evident. A boundary shown for the nineteenth century may have a different legal and cultural significance from a superficially similar line drawn for the late twentieth century.

Cartographers working alongside historians therefore faced the task of designing representations that preserved chronological distinctions without making the atlas impenetrable. The results contributed to a broader conception of map-making as an interpretative practice governed by evidence rather than merely the illustration of written narratives.

The partnership between the Academy's historians and the Department of Geomatics at the Czech Technical University continued through the Czech Historical Atlas project of 2016–2020. Its printed outcome, Czech Historical Atlas: Chapters from Twentieth-Century History, appeared in 2019, while the accompanying web portal was made publicly available in 2021. The project allowed historical topics not fully covered in the earlier atlas to be presented in digital form and in relation to a wider range of contextual material. In the online environment, a reader could move among maps, texts and illustrations, search for a subject and compare selected layers. This was a genuine change in the organisation of historical knowledge. The publisher no longer had to anticipate a single sequence of pages through which every reader would proceed. At the same time, the map designer acquired new responsibilities: navigation, the explanation of interactive functions and the consistency of a symbol when viewed under different conditions became part of the scientific presentation.

The Czech Historical Atlas demonstrated both the possibilities and the limits of interaction. Its web maps were not simply animated versions of printed plates. They allowed different evidence to be brought into view according to the reader's questions, and they could connect a location to explanatory commentary and imagery. Yet an interface that permits arbitrary combinations of layers can also encourage anachronistic comparisons. Historical cartography therefore requires controls over what may sensibly be compared, as well as an account of the dates and interpretations attached to each layer. The academic achievement was to make a substantial body of historical geographical scholarship available through a medium that invited exploration. Its success depended on maintaining the authority of carefully prepared content while allowing users a greater degree of choice. This distinction became central to the wider development of Czech interactive cartography: openness of navigation need not mean the abandonment of scholarly editorial responsibility.

Technical map services advanced through a different institutional route. As the Czech national geoportal developed, official geographical datasets and cartographic representations could be viewed through web applications rather than obtained only as physical sheets or specialised digital files. This changed the ordinary user's encounter with state cartography. A municipality could examine a place against an orthophoto; a researcher could consult topographic content without assembling the underlying database; and an interested citizen could compare landscape features across the country. Access through a browser did not remove the need for metadata, however. An image displayed as a base map is the visible result of particular source data, update cycles, coordinate systems and generalisation rules. The expansion of online services made the reliability of those invisible elements a public concern. A useful geoportal had to serve readers who could not be expected to know the technical history of every layer while still giving professional users the information needed to evaluate its suitability.

The relationship between a digital map and its source data became especially apparent in the transition to the newer state topographic map series. In July 2023, the Base Topographic Map at 1:10,000, designated ZTM 10, replaced the older ZM 10 series. The new map incorporated a revised approach to the presentation and generalisation of data drawn from ZABAGED and associated national sources. It was available within the established national coordinate system, while an ETRS89-based version was also introduced in 2023. The importance of this change did not lie only in the refreshed appearance of a familiar map. A new national series brought together questions of map sheet organisation, printing, digital distribution and the relation between reference systems. It showed that even in an era of continuous web mapping the state continued to maintain formally specified cartographic products. The printed sheet and the digital service were not rival forms of authority; both depended on a common process of selecting and depicting geographic information.

Czech map-making also had to respond to European approaches to sharing geographical information. European Union membership in 2004 and the INSPIRE directive adopted in 2007 placed increasing emphasis on interoperable spatial data, discoverable metadata and network services. The effects on cartography were gradual rather than instantaneous. National databases had been built for Czech surveying and mapping needs, and their objects, coordinates and update practices could not simply be relabelled to satisfy a European framework. Harmonisation required institutions to explain how their data corresponded to common themes and how users might retrieve and combine them. Once that work was undertaken, a map could draw more easily on services maintained by different authorities without requiring every organisation to duplicate the same source material. The scientific value was indirect but substantial: comparison became more reproducible, and cartographers could devote greater attention to the interpretation and appearance of thematic information. The framework also made the distinction between a data service and its visual portrayal more explicit.

New forms of distribution changed the practical economics of cartographic work. A printed atlas requires a production run and a stable edition, whereas a web map can be revised in stages and viewed from many locations. These advantages also introduce responsibilities that are less visible in a bound volume. An obsolete link can make a previously published map difficult to consult, and a layer that changes without an accessible archive may be unsuitable as evidence for a historical comparison. Czech institutions therefore faced questions of persistence, versioning and the documentation of updates. The continued availability of older official map sheets and orthophotographs supported the reconstruction of landscape change, while current services answered different, immediate questions. At a conceptual level, the change made time part of the map’s metadata. A geographer needed to know not only where a feature appeared but when the image or database represented it. This was a profound extension of the older obligation to state a map’s scale, projection and source.

The growth of private digital mapping formed a parallel history that influenced public expectations without replacing academic or state cartography. Commercial navigation systems and freely accessible consumer maps familiarised a wide audience with searchable addresses, route planning and automatically adjusted map scales. In the Czech Republic, the

development of locally relevant web services, including those associated with Mapy.cz, meant that many users came to regard a map as a tool for asking successive questions rather than as a fixed document. Road travel, hiking and urban orientation demanded different symbol hierarchies and levels of detail. These services made visible the importance of updating networks, maintaining place names and adapting representation to the screen on which the map was consulted. Their objectives were not always identical to those of scientific mapping, however. A routing application may privilege convenience and current accessibility, while a research map must preserve the provenance of its claims and permit them to be checked. The interaction between the two sectors broadened the standards against which Czech audiences judged map quality.

The familiar gestures of contemporary digital mapping—searching, zooming and turning layers on or off—altered the cartographic problem of scale. In a printed work, the chosen scale forms part of the published argument. In an interactive interface, users expect objects and labels to change as they move through scales, often without being conscious of the decisions involved. The cartographer must decide which roads remain visible, whether minor localities become more prominent and how a thematic classification behaves when the displayed area changes. A poorly designed multiscale product may create the illusion that all information has the same accuracy and relevance at every zoom level. The Czech development of base maps and thematic web applications made these issues increasingly familiar to cartographers and software developers alike. The underlying principle remained traditional: generalisation is necessary because no map can present all available geographical detail. Digital methods made the decisions more dynamic and required them to be encoded in repeatable procedures.

Alongside these changes, academic work on thematic cartography continued to refine the techniques by which complex spatial phenomena could be communicated. The 2011 volume Methods of Thematic Cartography: Visualisation of Spatial Phenomena, associated with Vít Voženílek, Jaroslav Kaňok and colleagues, provided a systematic treatment of representation that bridged established cartographic practice and modern geographic data. Its significance was methodological. A proportional symbol, choropleth, flow map or isoline diagram makes a different kind of claim about the geographical distribution of a variable. The suitability of each form depends on the data, the geographical units and the intended comparison. An interactive map does not make such distinctions obsolete; it may magnify the consequences of ignoring them. Teaching and research in Olomouc and elsewhere helped embed this reasoning in professional formation. The results supplied a vocabulary through which cartographers could discuss not just whether a map looked effective, but whether its graphic choices matched the structure of the phenomenon under investigation.

One of the most distinctive developments in Czech cartographic research was the growing effort to observe how readers actually interpret maps. The Department of Geoinformatics at Palacký University developed research in cognitive cartography, including eye-tracking experiments that recorded patterns of visual attention during map-reading tasks. Stanislav Popelka and colleagues investigated static and interactive displays, 3D representations and the influence of map complexity on reading strategies. This work challenged the assumption that a map designed according to established conventions would necessarily be understood

as its author intended. A map may direct the gaze towards a dramatic but secondary feature, or require too much effort to decode a legend before the reader can answer a simple geographical question. Experimental observation offered evidence for evaluating these problems rather than relying solely on professional intuition. It also introduced limitations of its own: looking at a feature does not prove that it was understood correctly. The methodological advance therefore involved combining evidence about attention with responses, tasks and the context in which a map was used.

Research into the perception of maps broadened the meaning of cartographic quality. Precision and consistency remained essential, but usability could be investigated in relation to real readers with different levels of experience. An unfamiliar symbol might be technically correct yet hard to recognise under time pressure, while a 3D scene could make one aspect of a landscape intuitive and obscure another. At Olomouc, studies of gaze trajectories, visual complexity and interactive behaviour gave cartographers tools for evaluating design choices. Such experiments did not yield a single universal recipe for successful mapping. Instead, they encouraged designers to specify what the map should allow a reader to discover, and to assess whether the chosen visual hierarchy supported that task. This was particularly relevant to educational maps and public-facing web interfaces, where users may lack the training required to compensate for ambiguous symbology. In this sense, the Czech work on cognitive mapping moved the discipline from a primarily producer-centred discussion of standards towards an evidence-based examination of communication.

The enlargement of visual media raised related questions about accessibility and public understanding. A paper map is read at a stable size under relatively predictable conditions, whereas a digital product may appear on a desktop display, tablet or mobile phone. Fine contours, small lettering and subtle colour differences do not retain the same legibility across these settings. Moving between screens may also change the context of interpretation, since the interface can occupy space otherwise available for a legend or explanatory notes. Czech cartographers and geoinformaticians increasingly had to reconcile graphic coherence with technical adaptability. This involved practical choices about contrast, label placement, the relative prominence of symbols and the amount of information presented at one time. For scientific maps, another consideration was the display of uncertainty: an interactive surface may seem precise simply because it can be enlarged. Clear accounts of data resolution, model assumptions and classification remain necessary even when the interface offers sophisticated controls. The best digital cartography thus continued to depend on the older discipline of making limitations intelligible.

Educational cartography was one of the fields in which continuity and change were most closely intertwined. School atlases and wall maps remained important in Czech classrooms throughout the period, while teaching increasingly incorporated digital layers, satellite images and interactive exercises. A school atlas is not a reduced scientific atlas; it is a designed sequence of concepts through which a reader learns to think geographically. Maps of relief, climate, population and transport should therefore be comparable without implying that their underlying measurements are identical. Digital tools enlarged the opportunities for students to examine scales and build simple thematic maps, but they also made it easier to copy a

visualisation without understanding its assumptions. Research and teaching at Czech universities helped prepare educators who could explain both the older graphic language of maps and the procedures through which new spatial images were produced. The lasting pedagogical question was whether a learner acquired the ability to interpret evidence, not merely the ability to operate a mapping application.

By the 2020s, Czech cartographic publication existed across a range of complementary formats. Official topographic maps continued to supply authoritative representations of national territory; scientific atlases offered edited syntheses; web portals allowed audiences to explore selected evidence interactively; and experimental visualisations tested how readers used unfamiliar displays. These forms differed in their update cycles, readerships and methods of quality control. Some benefited from frequent revision, while others required an edition to remain fixed so that a result could be cited and compared with later scholarship. The coexistence of formats was especially apparent in historical and environmental studies, where long observation periods and inherited records remained important. It would therefore be misleading to describe Czech cartography as having reached a final digital destination. Its development is better understood as the growth of a repertoire in which the choice of representation could follow the scientific question and the circumstances in which the resulting map would be read.

The country's cartographic achievements also depended on cooperation across professional boundaries. An atlas assembled from environmental data required experts who could judge the observations, statisticians who understood aggregation, and designers who could ensure a consistent visual argument. A historical web map brought together archives, historians, geomaticians and software developers. State topographic series depended on survey organisations and naming authorities, while cognitive cartography needed collaboration with disciplines concerned with perception and learning. Such cooperation was not automatically harmonious. Scientific specialists might seek exhaustive detail, whereas cartographers needed to exclude information to preserve legibility; software development might reward rapid iteration, whereas an archival publication required a stable record. The Czech experience between 1993 and 2025 demonstrates that these tensions were productive when they led to explicit decisions about sources, representation and readership. The capacity to discuss those decisions across institutions was itself an achievement of the modern research system.

Looking across the years from 1993 to 2025, the central transformation was a change in the relationship between the geographical record and its visual interpretation. At the start of the period, official map series, specialised atlases and archival collections were often encountered as distinct physical products. By its end, the same institutional system could sustain structured geographic databases, recurrently updated imagery, carefully edited national atlases and interactive research portals. ZABAGED and Geonames helped make state cartography more systematic; the climate, landscape and social atlases demonstrated the scholarly value of coordinated thematic synthesis; and historical atlas projects showed that new interfaces could widen access to evidence without removing the need for historical judgment. Research in cartographic cognition added a further question: whether the representation communicated what its designers thought it did. Together these developments

reveal the renewal of Czech cartography as a scientific field. Its continuing task is to make spatial evidence not merely visible, but interpretable, comparable and trustworthy.

Geographical Information Systems, Spatial Databases and Methods of Spatial Analysis

The history of geographical information systems in the Czech Republic begins with a problem that is older than the software used to address it: geographical observations have to be made comparable before they can become evidence about territory. In 1993, the new republic possessed detailed topographic and cadastral records, environmental measurements, statistical surveys and a substantial tradition of mathematical geography. Yet much of this information existed in separate institutional collections, on incompatible maps or in databases organised for purposes other than geographical enquiry. A river basin, a municipality and a cadastral parcel could each be described accurately without being readily compared with one another. The expansion of GIS therefore involved more than converting paper maps into digital images. It required common geographical references, methods of connecting attributes to places, rules for identifying change and research into the consequences of analytical choices. Between 1993 and 2025 these tasks turned geoinformatics into a research field in its own right and altered the questions that could be asked across Czech geography.

The transformation of the 1990s created both demand and opportunity. Municipal governments acquired wider responsibilities, private firms needed current spatial information, and environmental organisations began reassessing landscapes affected by industrial production and agricultural intensification. Universities could obtain geographical software and participate in international exchanges with fewer institutional constraints than before 1989. The main obstacle was not simply limited computing capacity. Data held by different public bodies were often described through different classifications and coordinate conventions, while field records lacked the metadata needed for comparison. An apparently precise overlay might join observations made at different dates or scales. Early practitioners consequently learned that operating a GIS and designing a defensible spatial analysis were distinct achievements. The latter depended on field knowledge, statistical competence and the ability to explain how the data had been assembled.

Ostrava became an early centre of this development. At VŠB–Technical University of Ostrava, a specialised geographical information systems course of study received approval in 1994, combining surveying, computer-based data processing and the analysis of geographical problems. The first GIS Ostrava meeting was also held in 1994; the event became a continuing forum for researchers, software specialists and users in public administration. Jiří Horák and colleagues helped establish an approach in which spatial databases, network models, location-allocation methods and statistical analysis formed a coherent technical curriculum. This location mattered. A former mining and industrial region presented demanding questions about land disturbance, infrastructure, labour markets and environmental exposure. These

problems supplied a practical setting in which spatial technologies could be evaluated against complex, imperfect records rather than demonstrated only on idealised datasets.

Olomouc followed a related but distinctive path. GIS and remote sensing were incorporated into geographical teaching and research during the 1990s, with a combined Geography–Geoinformatics programme introduced in 1997. A separate Department of Geoinformatics was established at Palacký University in 2001 under the leadership of Vít Voženílek. The department brought cartography, spatial modelling, environmental assessment and computer-assisted geographical methods into sustained contact. Its research eventually encompassed urban modelling, ecosystem functions, transport accessibility, spatial statistics and the communication of uncertainty. The institutional history illustrates why the emergence of geoinformatics should not be reduced to the arrival of commercially available software. A durable research field required laboratories, doctoral training, common terminology and a succession of projects through which methods could be improved and taught to new investigators.

At Charles University in Prague, the interaction between cartography, geographical analysis and the investigation of landscape change shaped another strand of research. The geographical section's work in applied geoinformatics and cartography connected digital databases with land-use history, environmental modelling and the interpretation of remotely sensed observations. The value of GIS was particularly visible when historical evidence had to be compared with contemporary measurements. A nineteenth-century map and a modern land-cover classification seldom describe exactly the same objects, and their boundaries cannot be assumed to correspond. The researcher must examine legends, georeferencing error, source dates and the limits of each classification before calculating change. In such studies, the database became an explicit record of interpretation rather than a passive store of mapped features. This approach helped preserve the geographical meaning of the archive within a digital analysis.

Other Czech centres developed complementary strengths. The University of West Bohemia in Plzeň cultivated geomatics and the design of interoperable spatial information systems, while Masaryk University in Brno drew on its traditions in physical geography, informatics and regional research. Czech Technical University in Prague connected GIS to engineering, surveying and cadastral information; technical universities and applied research institutes used geographical databases to investigate infrastructure and environmental risk. The differences were productive. Computer scientists could address indexing and efficient computation, surveyors could assess positional reliability, and geographers could establish which spatial relationships mattered for an explanatory problem. Joint work also exposed the danger of treating a universal software procedure as a universal geographical model. A technically correct intersection of two layers is useful only when the concepts represented by those layers can reasonably be combined.

One of the most important public foundations was the Fundamental Base of Geographic Data of the Czech Republic, or ZABAGED. Development began in 1995, and the initial national coverage of its defined geographical objects was completed in 2004. The database linked the geometry of settlements, roads, hydrography, land cover and other topographic features with

descriptive attributes. Its evolution from digitised map content towards a maintained, seamless spatial database changed the conditions of research. Instead of preparing an independent topographic base for every study, investigators could start from a common national representation. This increased comparability between projects and made it possible to examine the continuity of roads or rivers across former map-sheet boundaries. It also shifted attention to data lineage: knowing when a road was added or a river course revised became essential when the object of enquiry was change itself.

The significance of a common topographic database is easiest to understand through an apparently simple task. To estimate how many residents live within a given distance of a railway station, one needs the stations, a transport network, population information and a consistent spatial reference. If road connections are missing or buildings are geocoded only to an administrative centre, the result may differ substantially from everyday accessibility. ZABAGED helped supply the geographical framework, but analysts still had to decide whether distance meant a straight line, a walkable route or travel time. They also had to determine whether a station could actually be reached across a river or motorway.

Cadastral information added another source of geographical precision while raising distinct analytical questions. The information system of the real estate cadastre contained parcels and legal or administrative attributes organised for reliable registration, not for generalised geographical explanation. Linking these records to land use, planning designations or environmental observations could reveal patterns invisible in either dataset alone. Yet cadastral boundaries change, legal ownership does not determine actual land cover, and the detail appropriate for a property transaction may be unnecessarily revealing for social analysis. Czech GIS practice therefore had to distinguish the accuracy of an administrative record from the fitness of that record for a particular scientific purpose. The growth of digital cadastre services was important, but the analytical value came from carefully defined relationships between land registration and other spatial phenomena.

A second foundation was the gradual establishment of consistent territorial and address identifiers. The Register of Territorial Identification, Addresses and Real Estate, known as RÚIAN, began operating on 1 July 2012 alongside the basic registers of Czech public administration. It brought reference information about municipalities, territorial units, buildings, addresses and parcels into a system designed for reuse. The importance for spatial analysis extended beyond locating a building on a map. Stable identifiers made it easier to connect observations from otherwise separate administrative sources while recognising that the geometry and attributes of an object can change over time. For an analysis of service provision, disease incidence or demographic change, consistent geographical keys can be more consequential than a sophisticated visual display. They reduce the labour of reconciliation and make errors in territorial correspondence easier to identify.

The transition from records to interoperable databases was neither immediate nor complete. Czech geographical information commonly involved the S-JTSK national coordinate system, European terrestrial reference systems, historical map grids and remote-sensing products expressed in other projections. Transforming coordinates is a routine computer operation only after the source reference, relevant transformation method and expected accuracy have been

established. Confusion can arise when two datasets appear correctly located at a small scale yet differ by several metres in the field. More difficult still are conceptual inconsistencies: a settlement may be a built-up polygon in one database, an administrative unit in another and a statistical concentration of population in a third. The development of spatial data infrastructure made such inconsistencies more visible and encouraged systematic documentation instead of assuming that common coordinates implied common meaning.

Relational and object-based database design therefore became a central part of Czech GIS training and research. A geographical database has to preserve the relationship between a feature's geometry, its attributes and its identity through time. Spatial indexes permit efficient queries on large collections of polygons or lines, while topology rules can detect unclosed boundaries, overlapping parcels or broken network connections. Database transactions and controlled updates help maintain consistency when several institutions edit the same information. The scientific questions are not exhausted by technical architecture. An analyst deciding whether two stream segments constitute one watercourse must understand hydrological continuity; an analyst classifying a road must know whether its functional role or administrative designation is relevant.

The Czech Statistical Office offered an additional bridge between territorial registers and social research. The geographical identification of addresses and buildings made it possible to improve the allocation and presentation of population and economic statistics. Petr Klauda's discussion of site-oriented statistics in 2011 identified the potential of address-linked information for more consistent statistical production and geographical analysis. This was not a proposal to abandon administrative statistics. Rather, spatial identification could make the same observations suitable for different aggregations, including regular grids or functional areas that cross municipal boundaries. It became possible to ask how a population pattern looks when measured by neighbourhood, settlement or accessibility zone. Such flexibility also revealed the sensitivity of conclusions to the boundaries chosen for analysis.

This sensitivity is commonly described through the modifiable areal unit problem, but in the Czech setting it has a concrete institutional history. Many municipalities are small; some urban settlements are divided between local jurisdictions; and district boundaries have changed in administrative importance since 1993. A map of unemployment rates or educational attainment may appear very different when values are calculated for municipalities, districts or custom neighbourhoods. Small units can reveal local contrasts but may produce unstable rates when populations are limited. Larger units conceal variation and can make a diverse region appear homogeneous. Researchers increasingly treated the selection of an analytical unit as a methodological decision requiring justification. This was especially important when geographical results were being used to distribute public funds, identify peripheral areas or compare inequalities across successive censuses.

European integration intensified the need to exchange geographical information. The INSPIRE Directive of 2007 required member states to develop interoperable spatial datasets and network services to support environmental policy. In Czechia, CENIA acted as the national contact point and developed the National INSPIRE Geoportal during 2010–2012. Its work connected metadata, access services, data harmonisation and coordination among public

bodies. The project was not simply another national map viewer. A user needed to discover which organisation maintained a dataset, when it had been updated, what conditions governed reuse and how its features related to common European specifications. For scientific research, this infrastructure reduced the opacity of public spatial records, although access alone could not remove differences in observational quality or analytical purpose.

Metadata acquired particular importance as more data became accessible through web services. A layer titled ‘land use’ might represent cadastral categories, visually interpreted land cover or planning functions, each with different implications for analysis. A digital elevation model might derive from contour lines, photogrammetry or airborne laser scanning, with different error structures. A WMS service supplies an image suitable for viewing; a WFS service can provide geographic features that may be queried and analysed. Confusing a displayed map with its underlying data makes independent verification difficult. Czech implementation of geographical services therefore encouraged a more precise vocabulary of discovery, visualisation, download and processing. It also placed a continuing obligation on institutions to maintain metadata after the initial release of a dataset rather than treating documentation as a one-off administrative task.

The environmental applications of GIS were particularly diverse because Czech territory contains sharply contrasting landforms and histories of resource use. In the Ore Mountains, Jizera Mountains and industrial basins, spatial records helped relate air pollution, forest condition and land-use change. In lowland agricultural areas, they aided the assessment of erosion susceptibility, drainage, ecological networks and soil retention. The contribution of GIS was to make relationships between datasets testable at explicit spatial scales. A model could distinguish a steep cultivated slope from a nearby forested one, or compare settlements with different distances from industrial emissions. Yet interpretation still required knowledge of processes. The spatial coincidence of pollution and illness, e.g., could prompt investigation but did not establish a causal pathway without other evidence.

Soil and landscape analysis illustrated the increasing use of multi-criteria methods. Investigators combined terrain, soil properties, land cover and management conditions to identify sites where erosion or development pressures might be most serious. In the work of Vilém Pechanec and colleagues at Palacký University, geographical information became part of decision-support tools for evaluating ecological stability, retention capacity and economic considerations together. Their 2015 publication on landscape assessment set out a practical system in which different environmental criteria could be compared within one analytical framework. The methodological issue was how to express the relative importance of the criteria without disguising those choices as objective measurements. Testing alternative weights and classifications became as important as producing the final suitability map.

Landscape change supplied a long-term test of GIS methodology. Czech geographers could compare archival maps, aerial photographs, land-use statistics and contemporary satellite-derived classifications, tracing transitions between arable land, grassland, forests and built-up areas. The records, however, were not made for the same purposes. A historical cadastral map might describe ownership and taxation, while a modern remote-sensing product records spectral properties interpreted as land cover. Georeferencing a map does not eliminate its

original surveying error, and a boundary in an old legend may represent a category absent from the modern classification. Researchers such as Přemysl Štych and Lucie Kupková helped develop the analytical use of GIS in land-use and land-cover change studies at Charles University. Their work required explicit decisions about correspondence between sources, making historical comparison more rigorous and more open to revision.

The mathematical methods available to Czech geographers changed alongside the data. Earlier overlay analyses often used binary categories: an area was inside or outside a boundary, suitable or unsuitable for a specified use. With greater computing capacity, raster models, fuzzy membership functions and optimisation procedures made it possible to represent gradations. A place might possess characteristics of both urban and rural environments, or have a high ecological value alongside substantial development pressure. Such models were attractive because they reflected the ambiguity of real geographical categories. They also introduced decisions about threshold values, membership functions and the weights of different variables. The challenge was to keep those assumptions visible and test how robust the resulting geographical pattern remained when they changed.

An instructive example came from Vít Pászto, Alžběta Brychtová, Pavel Tuček, Lukáš Marek and Jaroslav Burian. Their study published in the Journal of Maps in 2015 used a fuzzy inference system to explore the rural and urban character of Czech municipalities in 2010. It responded to a problem created partly by suburbanisation: settlements did not always fit neatly into an urban–rural division based on a single administrative threshold. The method used several characteristics to represent intermediate degrees of membership, subsequently visualised in a national map. A related 2016 Geografie article examined municipal membership in rural and urban areas through a fuzzy-based approach. These papers demonstrated that GIS research could revise the categories used to explain geographical change rather than merely display categories established in advance.

Urban planning became a field in which the advantages and limitations of spatial modelling were especially visible. Local authorities faced pressure to accommodate housing and commercial development while protecting farmland, landscape continuity and transport capacity. A GIS could assemble constraints and opportunities within one territory and compare competing scenarios. The difficulty was not simply selecting parcels with the highest numerical score; it was deciding what constituted an acceptable compromise between development objectives. Urban planning involves legal restrictions, ownership, ecological processes and preferences that cannot be expressed through a single technical measure. Czech researchers therefore investigated decision-support models as instruments for structured discussion, not substitutes for political responsibility or professional judgement.

The Urban Planner extension developed by Jaroslav Burian, Stanislav Šťastný, Jan Brus, Vilém Pechanec and Vít Voženílek was a particularly clear contribution. Their 2015 Geografie paper explained a model of land-use suitability based on weighted raster overlay and assessed its operation in the Olomouc region. The method enabled alternative development scenarios to be constructed and their sensitivity examined. An area identified as favourable under one set of criteria might be less suitable when protection of agricultural land or transport accessibility received greater weight. Testing robustness was therefore central to the research, because a

planning recommendation should not be mistaken for an unambiguous result of computation. The project showed how the Czech GIS community could move from mapping existing urban structures towards modelling possible futures and making the underlying reasoning open to inspection.

The mapping of the changing built environment supplied a complementary, retrospective approach. Burian, Brus and Voženílek published an analysis of the development of Olomouc between 1930 and 2009 based on functional urban areas. By comparing the spatial distribution of activities across successive historical periods, they could identify changes that a general population total would not reveal. Housing, industry, public facilities and other functions spread or contracted according to different trajectories. Historical mapping and contemporary GIS met in a method that treated urban development as both a temporal and a spatial process. Its explanatory power nevertheless depended on knowing how the functional categories had been assigned in the original sources. A visually striking map of change remained only as reliable as those classifications.

Transport geography prompted increasingly sophisticated use of network analysis. Czech settlement patterns contain a dense network of small towns and villages, while mountain barriers, border crossings and the concentration of employment in major centres create pronounced differences in accessibility. A network-based model can estimate travel along roads or public transport lines, locate facilities in relation to their potential users and assess the effects of a new connection. Such modelling often begins with graph theory, treating intersections as nodes and road or service segments as links. Yet realistic estimates require direction restrictions, actual service schedules, transfer times and temporal variation. The growing availability of spatial databases allowed researchers to move beyond straight-line distance, although the need to validate network assumptions against observed travel behaviour remained.

The Ostrava school paid particular attention to spatial analysis of networks, location-allocation problems and geographical statistics. Jiří Horák's teaching materials and his 2019 volume Prostorové analýzy dat presented spatial analytical methods as a connected body of knowledge rather than a collection of isolated GIS commands. Applications ranged from statistical mapping of labour markets to transport accessibility and the selection of service locations. The emphasis on uncertainty was also important, as Horák's work on neurčitost v geoinformatice demonstrated. In a mining and industrial region, spatial datasets may contain both measurement uncertainty and ambiguities of definition. Understanding these limitations is vital when a model is used to compare neighbourhoods or assess whether a service network leaves particular populations without practical access.

Spatial statistics expanded the methodological scope of Czech GIS research. Two neighbouring municipalities often resemble one another more than two distant municipalities, violating the independence assumptions of many conventional statistical procedures. Measures of spatial autocorrelation help distinguish clusters from patterns that may arise by chance. Local statistics can identify concentrations that are obscured by a national average, while spatial regression models attempt to account for the geographical structure of the residual variation. In Czech applications, these tools have been used in analyses of population,

environmental conditions, economic inequality and public services. Their usefulness depends on selecting an appropriate spatial weights matrix and recognising that statistical association does not by itself establish the process responsible for a cluster. An apparent hotspot can also shift with the size of the study area or the choice of neighbouring units.

Point-pattern analysis contributed a different perspective. Individual events, businesses, observations of illness or environmental samples may be represented as points, but the distribution of those points is rarely independent of the opportunity to observe them. A cluster of recorded incidents near a hospital could reflect where people seek assistance rather than where a hazard originates. Kernel density estimation and distance-based functions are valuable summaries, not explanations in themselves. Czech training in geostatistics and event analysis increasingly incorporated questions of sampling, spatial intensity and interpretation. These questions became more pressing as researchers gained access to precisely geocoded records that gave an impression of resolution greater than the reliability of the underlying measurements. Greater positional detail can improve analysis only when accompanied by equally careful attention to why observations occur where they do.

Geostatistical methods were useful for variables measured at scattered sites, such as soil properties, rainfall or concentrations of a pollutant. Interpolation techniques could estimate values between observation points and produce surfaces for subsequent overlays. Methods based on variograms allowed investigators to examine the scale and direction of spatial dependence, while cross-validation could test the performance of an estimator against observations not used directly in a prediction. The temptation was to see the resulting smooth map as a complete description of nature. Czech research in environmental modelling offered many reasons for caution. Sampling networks were denser near roads or settlements, mountain terrain could alter relationships over short distances, and abrupt geological boundaries were not always represented by a smoothly varying function. A defensible map therefore needed to convey where predictions were well supported and where uncertainty remained substantial.

The treatment of uncertainty gradually became more explicit in GIS research. Errors arise from instrument accuracy, digitisation, georeferencing, classification, aggregation and the assumptions of spatial models. They can accumulate when datasets are joined. A small positional discrepancy may be negligible when mapping a regional climate trend but decisive when deciding whether a building intersects a narrow protected corridor. In Olomouc, Jan Brus and colleagues investigated uncertainty in environmental studies and its cartographic communication. In Ostrava, Horák examined uncertainty as a fundamental issue of geoinformatics. Their work encouraged researchers to distinguish measurement error from model uncertainty and conceptual ambiguity. Sensitivity tests, alternative scenarios and clear metadata could then become part of the result rather than technical details omitted from the published map.

The management of time formed another challenge. A geographical database may show the present position of roads and buildings, but it does not automatically preserve their previous states. Reconstructing the expansion of a city or the retreat of an industrial site requires the analyst to know not only what changed but also when the change entered the source record.

Administrative updates do not necessarily coincide with events on the ground. Pászto, Rostislav Nétek, Alena Vondráková and Voženílek made this problem concrete in their 2020 compilation of a harmonised municipal dataset for Czechia. Other applications depended on historical snapshots and dated documentary evidence. Temporal GIS brought new possibilities for identifying sequences, lags and recurrent patterns. It also made clear that the difference between two maps can include differences in survey method, not simply changes in the geographical world.

The introduction of web mapping changed the distribution of analytical work. In the 1990s, a GIS project often required specialised software and datasets installed on an individual computer. By the 2010s, geographical information could be explored through a browser, with layers requested from remote servers and combined in a client application. This expanded the potential audience to teachers, municipal officers, journalists and citizens. Yet the analytical capabilities of web viewers varied considerably. Some offered little beyond searching and display; others supported filtering, drawing, querying and export. It was therefore necessary to distinguish public access to a map from access to the data and methods that produced it. Interactive presentation could make evidence more approachable without necessarily making the underlying analysis reproducible.

Participation introduced a further change in the sources of geographical knowledge. A professional dataset records what institutions choose and are able to measure. Residents may know which pedestrian route feels unsafe, where seasonal flooding obstructs a path or which public space is valued despite its modest size. Geographical technologies can collect such knowledge through annotated maps, online surveys and community workshops. Jiří Pánek's research on geoparticipation developed these possibilities in Czech municipalities, including participatory mapping in Jeseník and the use of emotional maps. The resulting evidence differs from cadastral or topographic records: it describes experiences, preferences and perceptions rather than only physical objects. Its value rests on treating these responses as situated social information, not as replacements for engineering measurement or representative polling.

Pánek's 2018 study of participatory mapping in Jeseník and his wider work on emotional maps illustrated how the web could create a new kind of spatial dataset. Respondents could mark points or areas and add comments explaining the meaning of particular places. Researchers could then examine differences between groups or compare responses with the provision of public facilities. The approach opened a conversation between qualitative geographical knowledge and quantitative analysis. It also raised the question of who participated. Online consultations may overrepresent residents with reliable internet access, greater confidence in digital tools or a stronger incentive to respond. Interpretation consequently required careful description of the sample, the wording of questions and the ways in which responses were grouped on the map.

Municipal use of geoparticipatory methods became an empirical subject in its own right. A study by Pánek, Pászto, Burian, Jakub Bakule and Jakub Lysek published in 2021 constructed an index of geoparticipation using information from Czech municipalities and distinguished communication, participation and transparency. The work allowed researchers to ask whether larger cities or municipalities linked to particular development networks used these tools more

extensively. This was a significant methodological development. Rather than assuming that the availability of web technology meant local democratic engagement, it measured institutional practices and their geographical variation. GIS thus served both as a tool for participation and as a way to investigate the uneven adoption of participation itself. Such research connected geoinformatics with urban governance while retaining the discipline's interest in spatial differentiation.

The expansion of open-source software widened opportunities for experimentation. QGIS, spatial database extensions and scripting environments made it possible to develop workflows without restricting every user to a particular proprietary package. At VŠB–Technical University of Ostrava, teaching materials on Quantum GIS and the processing of labour-market statistics illustrated the effort to make specialist techniques accessible to analysts in other fields. Open software did not automatically guarantee reproducibility; tool versions, parameters and external datasets still had to be recorded. Its contribution was the possibility of inspecting and modifying workflows, sharing scripts and teaching students to understand analytical operations rather than memorise sequences of menu commands. During the 2010s and early 2020s, these practices increasingly complemented established desktop GIS within Czech research and public administration.

Geographical information also became more closely integrated with conventional statistical and programming environments. Analysts could construct automated processing chains, examine the effects of different parameter values and run calculations repeatedly as updated data arrived. This made large regional comparisons more feasible, especially when projects involved thousands of municipalities or fine grids. A script could document how observations had been filtered, aggregated and transformed, facilitating later inspection by another researcher. However, automation could also reproduce a mistaken assumption more efficiently across an entire dataset. The quality of Czech computational geography therefore depended on combining software engineering with domain expertise, version control and critical assessment of intermediate outputs. Reliable results required more than an executable script: they required an account of why each operation was appropriate for the geographical question.

The availability of more detailed mobility information opened additional avenues of research. Journey records, anonymised mobile-phone data and geolocated observations could supplement conventional commuting statistics or fixed transport timetables. They could reveal daily rhythms that population counts assigned to places of residence do not capture. Yet mobility datasets are produced for particular commercial or administrative purposes and may systematically exclude some users. A device observed in one area does not identify why its owner travelled there, while a recorded movement need not correspond to an actual journey by one person. Czech geoinformatics research increasingly had to confront these problems of representation as location data became more abundant. The analytical advance lay in the ability to compare several imperfect views of mobility rather than regard one high-resolution dataset as an unquestionable record of human behaviour.

Spatial analysis proved valuable in regional development research because economic and demographic phenomena rarely fit administrative borders neatly. Accessibility to employment,

schools and healthcare may depend on travel beyond a municipality's boundary, while service centres draw users from several districts. GIS can delineate catchment areas, compare alternative facility locations and identify communities with lengthy journeys to essential services. For Czech rural territories and internal peripheries, these methods supplied a way to distinguish geographical isolation from low population density alone. Two villages with similar populations may have very different opportunities because one is connected to a regional centre and the other lies beyond a mountain pass or poorly served transport corridor. Spatial modelling therefore enriched regional comparisons with information about relationships between places, not only attributes recorded within them.

Geographical research on public health and environmental exposure likewise benefited from the linking of location and statistical evidence. Mapping potential access to clinics, concentrations of air pollutants or the spatial distribution of health outcomes can identify questions for further investigation. Yet health records may require aggregation to protect confidentiality, and the resulting geography depends on where people live, work or receive services. An area with many registered patients is not necessarily an area with high disease risk. Czech researchers drawing on spatial epidemiology and environmental statistics had to manage small-number instability, confounding factors and the sensitivity of georeferenced personal data. The increasing power of GIS brought a corresponding responsibility to avoid turning a suggestive spatial association into an unsupported claim about causation or individuals.

The relationship between GIS and remote sensing became increasingly reciprocal. Satellite images and airborne observations supplied regularly refreshed information about the physical landscape, while GIS databases provided the reference features and contextual variables needed to interpret those images. A classification of forest condition might be evaluated using terrain, administrative boundaries, field measurements and earlier land-cover records. Conversely, new imagery could reveal that a geographical database had not yet recorded a road, building or vegetation change. This mutual dependence is distinct from the specialist development of sensors and 3D data considered elsewhere in this volume. For spatial analysis, the crucial achievement was the construction of workflows through which observations made by different instruments could become coherent evidence about one geographical process.

By the early 2020s, national data policy was further altering the conditions of GIS research. Czech public institutions increasingly offered standardised data services and reusable geospatial datasets, allowing analyses that once depended on negotiated access to be repeated more readily. The release of ZABAGED file datasets as open data in July 2023 was especially significant. Researchers and smaller public bodies could use a common topographic base without the same financial and procedural barriers that had previously constrained reuse. This improvement did not guarantee uniform data quality, but it changed who could undertake serious spatial analysis. A small research team could build a reproducible national study while directing more effort towards methods and interpretation rather than acquiring the basic geographical layers.

Open data also brought the question of stewardship to the foreground. If a scientific article depends on a national database, later readers need to know which version was used and

whether the relevant features have changed. A live web service may return different information several years after a study was conducted. Keeping an archived extract, recording download dates and describing licence conditions are therefore part of good scientific practice. Czech geoinformation institutions invested in identifiers, metadata and harmonised distribution precisely because data become more useful when their provenance can be traced. For long-term comparisons, the ability to reconstruct an earlier data state can be as important as rapid access to the newest version. A research infrastructure should preserve institutional memory as well as provide convenient current maps.

Education was an essential mechanism for spreading these methods beyond specialised laboratories. Graduates of Olomouc, Ostrava, Prague, Plzeň and other centres entered planning offices, environmental agencies, consultancies and research institutions. Courses combined programming, cartographic design, database management, spatial statistics and knowledge of geographical processes. Student projects offered an opportunity to test methods against datasets that could be incomplete, inconsistent or ethically sensitive. The GIS Ostrava conference and related scientific meetings helped circulate research between universities and practitioners, while doctoral programmes supported deeper methodological specialisation. A sophisticated national database has limited value if users cannot understand its geometry, metadata and constraints.

The growing use of GIS in public decisions exposed tensions between analytical transparency and the apparent authority of maps. A suitability map, flood-risk classification or transport-accessibility index can look definitive even when it rests on contestable modelling choices. Visual clarity and numerical sophistication may encourage decision-makers to overlook uncertainty. Czech studies of cartographic errors, spatial modelling and participation provided a counterweight to this risk. They showed that a useful geographical model must allow its assumptions to be challenged, and that a visualisation should communicate both the geographical pattern and the limits of what can be inferred. In practice, the strongest decision-support systems were those that made comparison between alternatives possible instead of presenting one technically generated answer as inevitable.

The main trends between 1993 and 2025 therefore cannot be summarised as a linear passage from primitive to advanced software. Czech geography gained an expanding set of common spatial databases, stronger national and European standards, specialised university research groups and a wider repertoire of analytical techniques. It also acquired clearer reasons to question its own outputs. The most fruitful projects combined administrative data with field evidence, examined multiple spatial scales and tested whether conclusions survived changes of classification or modelling parameters. GIS made cross-disciplinary collaboration easier because researchers could work with a shared geographical framework; it did not remove the need to understand what different disciplines meant by a forest, a settlement, a catchment or a region.

By the end of 2025, geographical information systems had become part of the everyday research environment of Czech geography, but they continued to generate scientific questions of their own. How should uncertain boundaries be represented? When can a spatial correlation be interpreted as evidence of a process? Which territorial units permit a fair comparison over

time? What responsibilities accompany the use of fine-grained information about people's activities? The Czech experience shows that these are not peripheral technical issues. They determine whether geographical databases and spatial models produce knowledge that can be trusted, challenged and reused. The period's enduring contribution was a closer connection between the careful construction of spatial evidence and the explanation of geographical change, a connection that supports both fundamental research and decisions about the future of Czech territory.

Remote Sensing, Aerial Observation and 3D Spatial Data

At the beginning of 1993, the newly independent Czech Republic inherited a landscape that had been photographed from the air, represented on topographic maps and intermittently examined through satellite images, but the various records did not yet form a unified digital account of change. Aerial survey had long served mapping and engineering, while photographs of forests, fields and industrial districts also preserved information that could not be recovered from written inventories. The scientific task after the political transition was therefore not simply to acquire more pictures. Researchers had to establish how images taken with different cameras, at different heights and under different illumination could support comparable measurements of the Earth's surface. They also had to devise ways of relating a remotely observed pattern to processes occurring on the ground. Over the following three decades, Czech remote sensing developed through the interaction of satellite observation, airborne survey, photogrammetry, field measurement and computer modelling. The outcome was a new capacity to study land-cover change and 3D structure over areas ranging from individual archaeological sites to the entire national territory.

The post-socialist restructuring of science altered the practical setting of this work. Universities renewed international partnerships, scientific laboratories gained access to commercial image-processing systems, and public mapping authorities gradually replaced analogue production with digital acquisition and editing. Costs remained a severe constraint in the 1990s: satellite scenes could be expensive, specialised instruments were scarce, and processing large raster datasets required computing resources not evenly available among institutions. Yet the opening of international scientific networks brought methodological literature and joint projects into Czech laboratories. The development of geographical information systems made remotely sensed observations more useful because image classifications could be compared with topographic, ecological and administrative records. Conversely, remote sensing forced GIS researchers to confront uncertainty in the source data from which their maps were assembled. The two fields became closely connected without losing their distinct scientific questions. A classification of land cover is an interpretation of spectral and spatial evidence, not a direct transcription of the landscape into a database.

Early university work in Prague linked established surveying traditions with experiments in satellite image analysis. At the Czech Technical University in Prague, Karel Pavelka's photogrammetric laboratory became a setting for research on image geometry, aerial survey

and the documentation of cultural heritage. Its involvement in a satellite receiving initiative during 1993–1997 and in work connected with CORINE Land Cover during the later 1990s illustrates the coexistence of technical measurement and environmental application. A remote-sensing image had to be corrected for sensor geometry and linked to a known coordinate system before it could be combined reliably with a cadastral or topographic map. The underlying problem was familiar to photogrammetrists, but digital methods required a new chain of processing decisions, from camera calibration to resampling and mosaicking. Studies of historical buildings also asked for more than a planimetric outline: researchers wanted to reconstruct surfaces, openings and complex structures. These lines of enquiry made Prague an important link between conventional photogrammetry and the emerging production of digital 3D information.

At Charles University, remote sensing grew particularly through geographical questions about vegetation, landscape structure and environmental change. The Faculty of Science provided a setting in which satellite observations could be interpreted alongside geomorphology, hydrology and land-use history. Researchers concerned with the Šumava mountains, e.g., needed to distinguish insect disturbance, timber harvesting and recovery in forests whose condition had political and ecological significance. Images acquired at several dates offered something that a single field survey could not: a view of the progression and spatial distribution of disturbance through time. Nevertheless, an apparent spectral change might result from atmospheric conditions, seasonal differences or the position of the sun rather than a transformation of the forest. This difficulty encouraged work on image normalisation, field validation and the definition of meaningful disturbance classes. It also showed why remotely sensed evidence had to be interpreted with local knowledge of forestry decisions, species composition and the history of the landscape.

The European CORINE Land Cover programme gave Czech researchers and environmental authorities a common framework for investigating changes in surface cover. Its inventories for 1990, 2000, 2006, 2012 and 2018 made it possible to compare agricultural land, forests, settlements and other categories using an established legend. Czech participation involved interpretation and checking of satellite imagery, supplemented by national geographical information and field knowledge. The value of the programme lay partly in the ability to relate changes inside Czechia to those recorded elsewhere in Europe. It also exposed the limitations of any standardised inventory. A mapped land-cover polygon may include several small features, and a transition in its classification does not by itself reveal the social or environmental mechanism responsible. At a broad scale, CORINE could describe conversion from agricultural land to urban surfaces; at the scale of a village street, it could not replace detailed aerial photographs. This distinction between mapping scale and explanatory claim became an enduring methodological principle.

Satellite archives became an instrument for examining the material geography of transformation after 1989. Industrial restructuring changed factory sites and mining landscapes, while the expansion of road infrastructure and dispersed suburban housing altered the boundaries of settlements. In agricultural districts, differences between extensive fields, vegetation cover and abandoned plots could be investigated by combining successive

images with land-register records. Researchers learned that an object may be spatially persistent while its use changes radically, or that a change in image texture need not signify a change in legal land use. The value of remote sensing was greatest when questions were framed at the outset: whether development had consumed previously cultivated soil, whether a disturbed forest had regenerated, or whether reclamation had altered a former mine. This movement from descriptive image interpretation towards problem-oriented change detection helped establish remote sensing as a component of geographical research rather than a subsidiary technology for making illustrations.

The Landsat programme furnished particularly important evidence because its long archive extended across the political and economic transitions. Images from successive sensors could be assembled into multi-decadal sequences, enabling the study of change that preceded the formal foundation of the Czech Republic. Such historical observations remained part of the evidence used for the 1993–2025 period, without making the earlier years the principal subject of the analysis. Comparative work demanded attention to differing spectral bands, pixel sizes, acquisition conditions and occasional gaps. A change observed between two dates might conceal a sequence of disturbance and regeneration, especially in a rapidly changing forest or wetland. The increasing availability of archival imagery therefore encouraged the use of longer time series and more explicit uncertainty assessment. For Czech geographical science, Landsat also established the principle that national research could depend on a continuously maintained international observation programme rather than on the purchase of isolated images.

The Šumava forests became a prominent demonstration of what time-series analysis could contribute. Martin Hais, Magda Jonášová, Jakub Langhammer and Tomáš Kučera compared spectral responses to bark-beetle disturbance and clear-cutting using Landsat observations and vegetation data in research published in 2009. Their work drew attention to differences in the temporal behaviour of disturbances that could appear superficially similar on a single image. A related study reconstructed disturbance dynamics over the longer period beginning in the 1980s, integrating remotely sensed records with the management history of the national park. Such studies did not resolve debates about conservation policy by themselves. They offered an independently repeatable account of where forest cover changed and how the changes progressed. That evidence made it possible to test claims about the extent of disturbance and the consequences of different management practices, while reminding readers that spectral signatures measure vegetation condition rather than the intentions of those managing it.

Airborne photographs retained scientific significance as satellite imagery became more accessible. In the Czech Republic, regular aerial surveying provided a record of roads, field boundaries, buildings and small landscape features at a spatial detail not consistently available from early satellite sensors. Analogue photographic negatives and prints could also be re-examined using modern scanning and geometric adjustment. This created an opportunity to recover historical observations for comparison with digitally acquired scenes. The transformation was technically demanding: camera orientation, ground control points and the characteristics of old photographic material all affected positional accuracy.

Orthorectification reduced image displacement caused by terrain and viewing geometry, but it could not make every historical photograph as accurate as a modern digital orthophoto. Consequently, researchers had to distinguish visible change from distortion introduced by the image source. The scientific importance of aerial archives grew as the demand for detailed landscape histories increased.

National orthophotography developed from a specialised mapping product into a widely used spatial reference. The Czech Office for Surveying, Mapping and Cadastre and the Land Survey Office maintained systematic aerial imagery and derived orthophotographic mosaics for territorial information systems. These products were especially useful because the images could be placed directly alongside digital cadastral and topographic layers. Their creation required control of flight planning, photographic overlap, image orientation, terrain data and colour balancing across adjoining scenes. A seamless orthophoto appears visually simple, yet the finished image rests on decisions about projection and the treatment of buildings, bridges, woodland and shadow. The increasing resolution of digital aerial photographs improved the observation of local change, but higher resolution also made small geometric errors and differences in acquisition dates more conspicuous. The national orthophoto programme therefore advanced both practical mapping and the measurement discipline needed for scientifically credible comparisons.

One of the clearest steps towards 3D national observation occurred with the aerial laser-scanning programme undertaken from 2009 to 2013. The Czech surveying administration worked with the ministries responsible for agriculture and defence to acquire elevation measurements across the country. Unlike a conventional photograph, an airborne laser scanner records ranges to reflecting surfaces and can produce a dense cloud of 3D points. The resulting observations nevertheless require classification: returns from ground, vegetation, roofs and other objects are not interchangeable. From this undertaking came the fourth-generation digital terrain model, DMR 4G, represented as a regular grid of elevation points, and the more detailed fifth-generation model, DMR 5G, in which a triangulated structure represents local variations in relief. A first-generation digital surface model, DMP 1G, represented the surface including features above the ground. These were different analytical products derived from a common measuring campaign, not merely successive resolutions of the same picture.

The new elevation models transformed the kinds of geographical questions that could be investigated at national and local scales. DMR 4G supplied a consistent terrain framework for regional modelling, broad infrastructure assessments and orthophoto production. DMR 5G preserved local variations that could matter in the interpretation of river valleys, earthworks, road embankments and small landforms. The digital surface model contributed information about buildings and vegetation, although its observation date and classification quality had to be considered. By the middle of the 2010s, nationwide access to more detailed elevation information had reduced the need to assemble inconsistent local surveys for every new study. The achievement was not simply a denser array of height values. It was the establishment of a measured and documented 3D foundation on which separate studies could be compared. Researchers could now place local field measurements in a national terrain context while remaining alert to the fact that the models represented particular moments in time.

The physical form of a digital terrain model also shaped the conclusions drawn from it. A regular grid is convenient for calculations of slope, aspect, visibility and overland flow, while a triangulated network can retain breaks of slope and irregularly distributed observations. Neither representation preserves every feature of the measured landscape. In a forest, only some laser pulses reach the ground; in urban areas, reflective surfaces, steep façades and narrow spaces can complicate the assignment of returns. The precision of an elevation model must therefore be considered separately from its resolution. A five-metre grid cell says how frequently heights are represented, not how close each height is to the true ground surface. Czech technical documentation was valuable because it described intended uses and errors instead of presenting the models as exact topography. The wider scientific lesson was that data density, terrain complexity, classification rules and the purpose of an analysis determine whether a 3D representation is suitable.

Airborne laser scanning also changed the interpretation of features concealed by vegetation. Small terraces, historic hollow ways, former field boundaries and earthworks can be easier to identify in ground-return terrain models than in photographs showing only the tree canopy. For archaeologists and landscape historians, this opened a way of examining the continuity between present woodland and earlier human use of a site. A terrain anomaly, however, is not automatically an archaeological feature. Modern drainage work, forestry tracks and natural erosion can produce forms resembling older constructions, and the scanning algorithm can create artefacts where point density is uneven. Responsible interpretation still requires comparison with historical maps, documentary evidence and, where appropriate, field investigation. Czech researchers and mapping institutions increasingly used the same 3D observations for divergent purposes, from hydrological analysis to heritage investigation. Their experience demonstrated the value of multipurpose national measurement, provided that later users understood the assumptions made during acquisition and processing.

The transition from photographic interpretation to digital photogrammetry brought another methodological change. Older stereoscopic methods relied on the geometrical intersection of image rays, carefully established camera parameters and skilled manual interpretation. Digital cameras, automated image matching and rapidly improving computing power extended these principles to dense surface reconstruction. A series of overlapping photographs could be used to estimate both camera positions and 3D points, provided that the image block had adequate geometry and control. Techniques commonly grouped under structure from motion made photographic reconstruction accessible to a broader range of investigators. Czech university laboratories used these methods to document architectural surfaces, excavation sites, riverbanks and terrain forms at a detail difficult to obtain from conventional maps. The appearance of a textured 3D model was not itself a guarantee of metric quality. The investigators still had to report control points, calibration, residual errors and limits imposed by reflective or poorly textured surfaces.

The Prague school of geomatics helped bring these methods into the investigation of cultural monuments. Karel Pavelka and Jan Řezníček described low-cost automated processing of digital photographs for heritage documentation in research published in 2011. Their emphasis on affordability addressed an important practical limitation: conservation organisations often

needed accurate records but could not maintain expensive scanning equipment. Digital photography offered a portable option, especially for inaccessible sites or objects requiring rapid recording. The resulting models could support measurements, drawings and visual explanation, though the suitability of a model depended on its calibration and on the geometry of the photographed subject. Work at the Czech Technical University also broadened into terrestrial laser scanning, mobile surveying and international heritage projects. By connecting mathematical photogrammetry with the needs of historians, architects and conservators, this research demonstrated how 3D observation could develop as a scientific service without abandoning its measurement foundations.

A different contribution emerged at Palacký University Olomouc, where the Department of Geoinformatics developed research on unmanned aerial systems and close-range photogrammetry. Jakub Miřijovský and colleagues investigated the production of detailed surface models from photographs acquired by small aircraft operating at low altitude. Such surveys could be repeated after a flood, landslide or episode of rapid vegetation change, avoiding some of the logistical and financial demands of conventional aerial campaigns. The department applied these methods to river morphology, forest regeneration, archaeological investigation and slope processes. Its research treated the planning of flights and the distribution of control points as scientific variables rather than routine preliminaries. Image overlap, viewing angle, vegetation movement and ground visibility influence how reliably a 3D surface can be reconstructed. The resulting body of work made Olomouc an important centre for investigating both the uses and the methodological limitations of drone-based observation.

River channels offered a demanding test of repeated photogrammetric surveys. Banks erode, bars migrate, vegetation grows and water surfaces interfere with image matching, while many geomorphological changes are too small to identify with coarse satellite imagery. Low-altitude photography permits researchers to compare detailed models of exposed riverbed and adjacent floodplain areas across successive surveys. The scientific challenge lies in ensuring that apparent differences are larger than the combined errors of the surveys being compared. A minor displacement of control points or a different reconstruction of a water-covered surface can resemble erosion or sediment deposition. Czech investigations of the Morava and other rivers illustrated why geomorphological interpretation must follow a careful accounting of positional uncertainty. Drone photogrammetry made repeated measurement more feasible, but also multiplied the number of images and processing choices that required quality control. The method consequently strengthened links between field geomorphology, photogrammetric mathematics and spatial analysis.

Slope instability provided a related application in the hilly and industrially altered landscapes of Czechia. Landslides may develop through slow deformation before conspicuous movement occurs, and their extent is not always adequately captured by a small number of ground instruments. Terrestrial laser scanners and unmanned aircraft can provide surface observations distributed across an entire slope. Comparing point clouds, elevation differences or reconstructed surfaces can reveal changes in shape, subject to the accuracy of registration and the persistence of vegetation. Yet not every observed difference reflects ground displacement. Leaves, temporary objects, shadows and changes in visibility can produce

misleading patterns. Research groups working with geologists and engineers therefore learned to combine remote surveys with direct measurements and knowledge of subsurface conditions. Such work expanded the use of 3D data from the creation of static representations to the analysis of evolving hazards, while preserving the distinction between surface movement and its geological cause.

Mining regions presented a particularly strong reason to connect remote sensing with field expertise. In northern Bohemia and the Ostrava–Karviná area, extraction, waste deposition and subsequent reclamation altered landforms over decades. Photographs and satellite scenes could reveal changes in vegetation and the outline of disturbed ground; elevation surveys could quantify changes in surface form and the creation of artificial landforms. Satellite radar interferometry provided another form of evidence by detecting changes in the distance between a satellite and the observed surface over repeated acquisitions. Such measurements can help identify subsidence, but they respond to movement in a particular viewing direction and depend on persistent radar targets. Researchers therefore had to distinguish true ground motion from atmospheric delay, surface-cover change and loss of interferometric coherence. The interaction of these methods created a richer account of post-industrial landscapes than would have been possible from any single sensor.

The growing European space-observation system strengthened Czech research capacity. Czechia signed a cooperation agreement with the European Space Agency in 1996, entered the Plan for European Cooperating States in 2004 and became a full ESA member in November 2008. These institutional steps were relevant to Earth observation because they increased opportunities for scientific participation, technical development and access to joint programmes. They did not immediately transform every university laboratory into a satellite research centre, and the benefits were mediated by personnel, funding and specialised expertise. Nevertheless, the connection placed Czech researchers in a wider network concerned with instrument calibration, environmental products and comparable monitoring methods. The later availability of Copernicus observations extended this connection into everyday research practice. Increasingly, an investigator in Brno, Prague or Olomouc could use data produced through a continental infrastructure while contributing local measurements and methodological expertise to their interpretation.

The Copernicus programme changed the temporal rhythm of observation. Landsat had already established the value of consistent archives; the Sentinel satellites provided additional spectral, radar and revisit capabilities that made repeated assessments of Czech landscapes easier to organise. Optical images were useful for vegetation condition and surface-cover classification, although clouds remained a persistent limitation in Central European weather. Radar observations offered a complementary signal sensitive to surface roughness, moisture and geometric conditions, without depending on daylight or cloud-free skies. The interpretation of radar imagery was not interchangeable with that of optical bands, and integrating them required clear assumptions about what each sensor measured. Czech studies increasingly combined several dates and sensor types rather than relying on a single visually appealing acquisition. The scientific benefit lay in moving towards continuous

monitoring, where observations could identify the timing and trajectory of change, not merely establish that an area looked different before and after an event.

Brno became a major centre of advanced environmental remote sensing through the Global Change Research Institute of the Czech Academy of Sciences, widely known as CzechGlobe. Its Department of Remote Sensing developed a programme linking vegetation ecology, imaging spectroscopy, airborne sensors and 3D models. The institute's Flying Laboratory of Imaging Systems brought together hyperspectral imaging, thermal observation and laser scanning in a coordinated aerial platform. These instruments measure different properties of the same landscape: reflected radiation in narrow spectral bands, emitted thermal energy and the 3D geometry of surfaces. Their simultaneous or closely coordinated use reduces uncertainty caused by observing an ecosystem under substantially different conditions. Researchers including František Zemek, Jan Hanuš, Lucie Homolová, Petr Lukeš, Jan Novotný and their colleagues explored how these measurements could describe forests, crops and urban environments. The resulting work was distinctive because it joined instrument development with detailed ecological questions and independent field validation.

Imaging spectroscopy was a significant methodological step beyond conventional multispectral mapping. A narrow spectral band may contain information about leaf pigments, water content or other physical and biochemical characteristics, but the relationship is rarely unique. Variations in leaf angle, canopy density, soil background and illumination can produce similar changes in reflected radiation. CzechGlobe scientists used field spectroscopy and radiative-transfer models to examine these ambiguities and to test methods for estimating vegetation traits across scales. Lucie Homolová's research linked leaf-level optical measurements to the characteristics of forest and grassland canopies, while collaborative work considered how results from laboratory, field, airborne and satellite observations could be made compatible. The scientific contribution consisted not in claiming that a spectral index directly measured tree health, but in specifying the circumstances under which optical evidence could support an ecological estimate. This approach helped integrate remote sensing with plant physiology and environmental monitoring.

The Bílý Kříž ecosystem research site in the Beskydy mountains provided a valuable setting for this integration. Measurements of spruce forest structure and physiology, collected in situ, supplied reference information for testing interpretations of remote observations. Work by Homolová, Růžena Janoutová, Lukeš, Hanuš, Novotný, Olga Brovkina and colleagues presented the site as a basis for evaluating forest parameters inferred from remote sensing. The value of such a station extends beyond any one experiment because it enables repeated comparison of sensor products with observed canopy properties. Yet a mountain spruce stand is not a universal representation of all Czech forests. Differences in species composition, management, stand age and environmental stress can alter the relation between observed spectra and biological properties. The Brno research programme therefore made transferability itself a subject of study. This was a fundamental advance over simply validating a map at a few convenient points and treating the resulting accuracy as fixed across the country.

The combination of hyperspectral images and laser data made it possible to connect canopy chemistry with forest structure. Optical information helps distinguish materials and physiological conditions, while lidar describes crown height, shape and the vertical distribution of reflecting surfaces. Investigators at CzechGlobe tested methods for segmenting individual crowns, separating species and estimating biomass. A 2015 study by Olga Brovkina, František Zemek and Tomáš Fabiánek examined above-ground biomass estimation using airborne hyperspectral and lidar observations in the Těšínské Beskydy mountains. Related work assessed the potential of satellite hyperspectral imagery for classifying forest species and evaluated how airborne and field observations could support that interpretation. Such studies illustrated why a fusion of data types can be more informative than simply increasing image resolution. At the same time, they revealed uncertainty associated with overlapping crowns, uneven point density and the representation of smaller trees beneath the visible canopy.

The bark-beetle disturbances of the late 2010s gave these methods an urgent practical setting. Large areas of spruce forest experienced damage, and observers needed to distinguish early stress, active infestation, dead canopies and subsequent management or regeneration. In research published in 2021, Vojtěch Bárta, Petr Lukeš and Lucie Homolová investigated the early detection of bark-beetle infestation using Sentinel-2 observations. Their work exemplified a shift from mapping the visible aftermath of disturbance towards identifying changes that might be useful before damage was unmistakable from the ground. A separate comparison of field surveys and remote-sensing methods examined the conditions under which affected trees could be detected. The operational value of such studies depended on error rates and the time available between detection and intervention. A method that identifies severe damage accurately may still fail to distinguish subtle early symptoms from drought stress. Czech forest monitoring therefore became an arena in which scientific accuracy had immediate consequences for the interpretation of environmental risk.

Satellite and airborne data also advanced the assessment of regeneration after disturbance. A cleared or damaged stand can produce a distinctive spectral response, but the later appearance of green vegetation does not establish that a functioning forest has recovered. Grass, shrubs and young trees may contribute differently to reflectance, while their ecological roles change as the stand develops. 3D observations can add information about canopy height and structural diversity that cannot be inferred reliably from greenness alone. Studies of succession in Šumava and other mountain forests therefore benefited from a combination of time-series imagery, detailed aerial surveys and ecological monitoring. Researchers had to distinguish forest recovery as a change in land-cover class from recovery as a process involving age structure, species composition and resilience. The more sophisticated the observations became, the clearer it was that the meaning of a remotely sensed indicator depended on the environmental question. This reasoning provided a bridge between technical image analysis and longer-term landscape ecology.

Agricultural observation followed a related trajectory. Early remotely sensed studies often mapped cultivated land and broad differences in vegetation cover; later research addressed crop condition, seasonal development and the distribution of water or nutrient stress.

Hyperspectral and multispectral observations could help identify spatial variation within fields, while thermal measurements offered evidence about the temperature of plant canopies. CzechGlobe research on plant traits and crop productivity combined satellite time series, modelling and field measurements to improve estimation rather than treating a single index as a direct measure of yield. A field is not spectrally uniform, and the timing of acquisition matters as much as spatial resolution. Soil exposure, crop variety, management practices and rainfall can change the observed signal during a growing season. Studies produced towards the end of the period increasingly explored machine-learning methods, but their usefulness depended on training data that represented the conditions in which a model would be applied. The result was a more quantitative and cautious approach to precision agriculture.

Drought research further demonstrated the importance of combining observations from different domains. Optical imagery can register changes in vegetation condition, thermal measurements can indicate differences in surface temperature, and meteorological observations describe the atmospheric demands placed on plants and soils. None of these, on its own, measures the full water balance of a catchment or an agricultural landscape. Czech researchers therefore brought remote sensing into contact with hydrological modelling, field measurements and national drought-monitoring initiatives. This integration was especially important during the prolonged dry conditions experienced in parts of Central Europe during the 2010s. Observed vegetation stress had to be interpreted against soil properties, previous rainfall and the timing of plant growth. It also had to be separated from changes caused by harvesting or land management. The contribution of remotely sensed products lay in offering spatial continuity between ground stations while retaining the need for independent data about the processes producing the observed pattern.

Urban remote sensing became more prominent as Czech cities experienced suburban expansion, redevelopment and intensified concern about heat. High-resolution aerial photographs helped trace the replacement of open land by buildings and paved surfaces, while thermal observations revealed contrasts between vegetated areas and densely built-up districts. The Department of Remote Sensing at CzechGlobe included urban thermal processes among its research interests, linking surface observations with questions of town planning and human well-being. Such work required careful distinction between land-surface temperature and the air temperature experienced by a person in a street. A satellite or airborne thermal image records emission from visible surfaces at a particular time; it does not directly reconstruct the full urban microclimate. Shading, wind, building geometry and seasonal conditions all affect the interpretation. By combining remote sensing with 3D urban form and ground measurements, researchers could investigate why neighbourhoods differed in heat exposure and identify limitations of simplified greenness-based explanations.

The emergence of realistic 3D city representations brought additional opportunities and problems. Buildings reconstructed from dense imagery or laser scanning can support studies of shading, line of sight, surface area and the spatial relation of streets to surrounding structures. Yet a visual model made for public display may not contain the geometric precision, semantic classification or acquisition history needed for scientific work. Researchers increasingly distinguished a textured surface mesh from a structured urban model in which

buildings, terrain and infrastructure are identifiable objects with defined attributes. Czech national and regional mapping initiatives, including developments in digital technical mapping during the 2020s, created conditions for stronger links between measured geometry and administrative information. Those systems had practical statutory purposes and were not themselves equivalent to scientific remote sensing. Their significance was that survey-grade spatial records could be combined with observations acquired from the air, provided that data quality, update cycles and legal restrictions were properly understood.

Archaeology and architectural history offered another field in which 3D data changed the questions being asked. Detailed models made it possible to examine construction geometry, document damaged surfaces and compare an object before and after conservation work. Work at the Czech Technical University in Prague extended from photogrammetric images to terrestrial scanning and mobile systems; research by Karel Pavelka Jr and Jan Pacina, published in 2023, described the application of these technologies to heritage visualisation in an international project. Such examples illustrated the portability of Czech geomatics expertise and the value of combining multiple instruments when access is restricted. Nevertheless, a reconstruction records what was measurable at a particular moment, not necessarily the historical form of the monument. Missing surfaces, later additions and material deterioration demand interpretation beyond the point cloud. Conservation science benefited most when a geometrically documented model was accompanied by evidence on materials, chronology and the conditions under which observations were obtained.

The International Society for Photogrammetry and Remote Sensing held its 2016 congress in Prague, an event that provided a visible setting for exchanges between Czech researchers and specialists from elsewhere. Conference papers associated with the meeting addressed satellite imaging, digital reconstruction, sensor comparison and increasingly automated workflows. One Czech-linked contribution investigated the potential of the Resurs-P hyperspectral satellite for forest-species classification, comparing it with airborne measurements and field spectra. Its importance was methodological rather than a claim that one instrument could replace all the others. Satellite observations provide spatial reach, airborne instruments offer flexibility and detail, and field spectroscopy provides reference measurements under controlled conditions. The Prague congress reflected a field becoming increasingly international in its terminology, datasets and quality standards. At the same time, contributions by Czech laboratories retained their connection to specific research landscapes and institutional capabilities. This combination of common methods and locally grounded questions characterised the maturation of the discipline.

A particularly clear synthesis of airborne methods appeared in 2023, when Jan Hanuš and colleagues documented the Flying Laboratory of Imaging Systems and the fusion of hyperspectral observations with laser scanning for ecosystem research. The publication made the acquisition infrastructure and its methodological possibilities more visible to international readers. It also illustrated a change in the meaning of an airborne campaign. Instead of collecting a single image that would later be interpreted in isolation, a modern flight could form part of a coordinated experiment involving several sensors, calibrated field instruments and ecological models. The value of the combined dataset rested on synchronisation, spectral

calibration, navigation and the assessment of measurement uncertainty. This was a demanding form of research infrastructure, dependent on specialised staff and long-term maintenance as well as on aircraft and sensors. By 2025, CzechGlobe's airborne programme represented one of the strongest examples of how national scientific investment could support both fundamental ecosystem research and practical environmental assessment.

Across the Czech research system, the increasing abundance of observations shifted attention towards reproducibility. A remotely sensed map could be generated by several algorithms, each involving decisions about atmospheric correction, training samples, segmentation, classification thresholds and post-processing. Different analysts working with the same images might obtain different boundaries or estimates. 3D reconstruction introduced comparable choices in image alignment, filtering, ground-point classification and the treatment of uncertain surfaces. Publications began to explain these procedures more explicitly because scientific results had to withstand comparison beyond the laboratory that created them. International archives and open-data policies improved access to observations, but the ability to reproduce a conclusion still required information about software versions, reference data and validation methods. Czech researchers contributed to this wider methodological discussion through studies that compared sensors and analytical approaches rather than presenting a single technically successful map as sufficient proof of accuracy.

The ethical and organisational dimensions of remote observation also became more visible. Aerial surveys can contain identifiable details of buildings, infrastructure and everyday activities, while high-resolution models of archaeological or strategic sites may have restrictions on publication. Scientific openness must therefore be balanced against privacy, conservation and legitimate security considerations. Drone operations also depend on airspace regulation, flight safety and permission to survey certain sites, and these constraints can influence the feasibility of repeated measurements. The increasing use of commercial cloud processing and machine learning raised additional questions about continuity of access and long-term stewardship of analytical workflows. Czech institutions had to consider how a dataset would be documented, stored, corrected and made intelligible after the original investigators had moved on. These questions did not replace the technical sciences of photogrammetry and image analysis. They extended the definition of reliable scientific observation from the accuracy of an individual measurement to the responsible maintenance and interpretation of the evidence produced.

By the end of 2025, Czech remote sensing and 3D spatial observation had developed into a diverse research domain with complementary institutional strengths. State mapping authorities supplied systematic aerial imagery and elevation products, universities advanced photogrammetric methods and local-scale applications, and Academy of Sciences teams integrated satellite and airborne measurements with environmental experiments. Prague contributed particularly to precise reconstruction and heritage documentation, Olomouc to unmanned aerial photogrammetry and landscape process studies, and Brno to advanced imaging spectroscopy, lidar and ecosystem research. These were overlapping tendencies rather than rigid divisions of expertise. The most consequential methodological achievement was the ability to move between scales while testing what each observation could legitimately

establish. A satellite time series might reveal the extent of a disturbed forest, an aircraft could describe its spectral and structural variation, and field measurements could explain the physiological state of selected trees. Together, these approaches transformed remote observation from a source of maps into an increasingly integrated science of spatial change.

Geospatial Research Infrastructure, Data Accessibility and the Integration of Scientific Information

The development of geospatial research infrastructure in the Czech Republic between 1993 and 2025 was not simply the conversion of analogue maps into digital files. It involved the gradual construction of a shared informational environment in which surveyors, geographers, geologists, environmental scientists, statisticians and public authorities could describe the same territory through compatible, although not always identical, systems of reference. At the foundation of this transformation lay an institutional question: who should collect spatial information, maintain its reliability, establish conditions for its use and preserve it beyond the lifetime of a particular investigation? The answer changed as computational capacity expanded, the country entered European regulatory frameworks and public expectations of access increased. Geospatial data consequently acquired a double identity. They remained evidence produced by specialised scientific and administrative practices, while becoming reusable infrastructure upon which further knowledge could be constructed.

In 1993 the newly independent Czech Republic inherited an extensive tradition of topographic mapping, geodetic control, geological documentation, cadastral records and environmental observation. The inherited collections were intellectually rich but organised principally around the needs of particular institutions and the physical products they issued. A map sheet, a survey report or a register entry had a recognisable custodian and a relatively stable purpose. Combining several such sources for a new research question could demand substantial manual interpretation, conversion of coordinates and reconciliation of classification systems. The post-socialist transformation introduced more diverse property relations, newly empowered local authorities and an expanding range of private users, increasing demand for spatial information outside its original administrative setting. The problem was therefore not an absence of geographical knowledge, but the limited mobility of that knowledge across organisational and technical boundaries.

Early computerisation often followed the structure of existing departments. Specialist units purchased software, digitised material most urgently required for their work and developed databases whose internal logic reflected established professional methods. These initiatives enabled quicker processing and more sophisticated analysis, but they could also reproduce the fragmentation of earlier archives in electronic form. A settlement boundary drawn for statistical reporting might not coincide exactly with a cadastral boundary; the location of an environmental sampling point might be recorded in a coordinate system unfamiliar to a municipal planner. Such discrepancies were not necessarily errors. They resulted from

differing scales, definitions, acquisition dates and responsibilities. Czech geoinformatics gradually learned to treat these differences as properties requiring documentation and management rather than as inconveniences that software alone could erase.

A research infrastructure in this setting consisted of more than computers, servers and telecommunications. Its essential elements included reference datasets, observation networks, agreed methods of describing information, systems for preserving updates, stable institutional responsibilities and rules for requesting or redistributing results. The distinction matters historically because a sophisticated digital map does not, by itself, provide dependable infrastructure. It may become obsolete when its producer changes software, or misleading when the user cannot discover the date, positional accuracy or legal status of the underlying observations. The transition from discrete projects to services capable of sustained operation was consequently one of the principal achievements of the period. It shifted attention from the production of individual outputs towards stewardship of a continuously evolving body of spatial evidence.

One of the most important foundations was the Fundamental Base of Geographic Data of the Czech Republic, known as ZABAGED. Work on the database began in 1995, initially drawing on the vectorisation of large-scale state topographic material, and the defined national coverage was completed in 2004. Its significance lay less in the replacement of paper sheets than in the movement towards a seamless digital representation of topographic objects across the national territory. Roads, waterways, buildings, vegetation and other landscape features could increasingly be treated as elements of a maintained geographic database rather than independent symbols on adjacent maps. This made the data useful for applications not envisaged when the original cartographic documents had been compiled. The maintenance of ZABAGED by the Land Survey Office also gave researchers an identifiable authority for national topographic reference information.

The production history of ZABAGED illustrates how infrastructure emerges through revision rather than through a single act of digitisation. The early database had to be completed, checked against aerial imagery, corrected through field investigation and supplemented by descriptive attributes. Updating subsequently incorporated information from public authorities and other recognised sources, with some rapidly changing objects requiring more frequent attention than the general revision cycle. This arrangement established a relationship between national cartographic responsibility and observations created elsewhere. It also exposed a central issue in data integration: an authoritative layer is valuable only when its users understand which objects are represented, how they are defined and how recent the corresponding records are. Accuracy, completeness and temporal currency became distinguishable dimensions of quality rather than a single general claim to reliability.

National map production provided further layers of shared reference. Digital geographic models intended for smaller scales, orthophotographic mosaics and progressively improved terrain models served different analytical requirements. Researchers studying the distribution of settlements or the structure of regional transport could work with generalised representations, whereas investigations of erosion, infrastructure corridors or flood pathways required considerably finer geometry. The importance of maintaining several levels of detail

was sometimes obscured by the apparent freedom of digital zooming. Enlargement on a screen does not increase the original informational resolution of a dataset. Czech geospatial services therefore had to explain scale, generalisation and appropriate use alongside the technical possibility of display. These qualifications remained especially important when users combined national background maps with much more precise local observations.

The geodetic reference framework gave these collections their common spatial grammar. National coordinates based on the Czech surveying tradition continued to coexist with European and global frames required for satellite positioning and international exchanges. The System of the Unified Trigonometrical Cadastral Network, commonly designated S-JTSK, and the Baltic vertical datum after adjustment retained practical importance, while ETRS89 and European vertical references facilitated interoperability beyond national borders. Transformation between frames was never merely a cosmetic change of labels. Geometrical discrepancies could arise through projection choices, historical control, transformation parameters and the accuracy of the original survey. For a regional overview such effects might be modest; for engineering or precise environmental monitoring they could alter the interpretation of results. Reliable coordinate transformations were thus part of the invisible infrastructure supporting multidisciplinary research.

The arrival of extensive elevation data expanded the functional meaning of national reference information. A programme of airborne laser scanning conducted between 2009 and 2016, in cooperation between surveying, agricultural and defence authorities, produced new digital representations of terrain and surface features. Among its outputs were the fourth- and fifth-generation digital terrain models and an initial digital surface model. These datasets allowed investigators to assess slope, drainage direction, visibility, local relief and built or vegetated surfaces with a consistency not previously available across the whole country. Their scientific value, however, depended upon processing decisions, classifications of returns and documented measures of precision. Terrain data became a common input into hydrological, geomorphological and planning models, but interpretation still required attention to the conditions under which a digital surface could stand for physical terrain.

Orthophotographic coverage supplied another bridge between authoritative mapping and direct observation of landscape change. Images corrected to a geographic reference could be combined with vector boundaries, used to revise topographic features and inspected by researchers seeking traces of construction, forest disturbance or changes in agricultural management. Their apparent immediacy did not eliminate uncertainty: seasonal vegetation, shadows, image acquisition dates and the difference between visible cover and legal land use complicated interpretation. Nevertheless, regular national coverage provided a shared visual record to which different disciplines could return. Its value increased as web services made imagery available without requiring each institution to purchase, store and process complete national mosaics. The transition from a delivered product to a maintained service changed both the economics and the routines of spatial research.

The cadastral and territorial identification systems formed an equally consequential, though conceptually different, part of the infrastructure. A topographic database describes physical features according to cartographic conventions; an administrative register records entities

whose legal or organisational identities must remain stable through particular changes. The Register of Territorial Identification, Addresses and Real Estate, RÚIAN, became operational on 1 July 2012 as part of the Czech system of basic public registers. It brought territorial elements and addresses into a framework designed for wider administrative reuse. The Czech Office for Surveying, Mapping and Cadastre administered the register, while authorised bodies contributed changes through dedicated editing arrangements. For geographers, the resulting infrastructure made it easier to relate observations to settlements, administrative divisions and address locations without constructing a separate territorial dictionary for every project.

RÚIAN also illustrated why identifiers can be as important as coordinates. Coordinates locate an object at a particular moment, but a stable identifier can connect statistical, administrative and spatial records even when a name or boundary changes. This is indispensable in a country where municipalities, cadastral units, districts and other territorial categories have distinct histories and analytical purposes. The register's exchange formats, public remote access and subsequently accessible services made standardised territorial information available for repeated use. Yet a researcher still had to distinguish the identity of an administrative element from the geometry used to represent it. Comparing population data across changing territorial units, e.g., required either harmonised spatial units or an explicit method for allocating observations across boundary revisions.

The national infrastructure was not built by surveying authorities alone. The Czech Environmental Information Agency, CENIA, developed an important coordinating and service-providing role at the intersection of environmental administration and geoinformatics. Its work included the management and publication of environmental spatial information, metadata services and the operation of the national INSPIRE geoportal. The value of this institutional function lay in its breadth. Environmental research generates datasets across hydrology, air quality, land cover, waste, protected areas and numerous other subjects, often through organisations governed by different legislation. A common discovery environment allowed users to identify available resources without assuming that all data originated from one central repository. Such an approach preserved specialist custodianship while encouraging exchange through shared interfaces.

As environmental data became more accessible, their scientific interpretation required attention to provenance. A dataset on protected habitats, a geological map and a hydrometeorological measurement network may all be displayed on a single map, but each represents a different evidential practice. Habitat records depend on survey classifications and observation effort; geological polygons summarise expert interpretations of subsurface materials; station measurements reflect instrument location, calibration and temporal sampling. A geoportal can bring these resources into visual contact without resolving their conceptual differences. Czech researchers therefore faced a task that was epistemological as well as technical: deciding when such information could be integrated for inference, when it should only be juxtaposed and when uncertainties had to be communicated explicitly to users outside the originating discipline.

The European Union's INSPIRE Directive, adopted in 2007, supplied a decisive legal and technical framework for this evolution. Its purpose was to establish infrastructure for spatial

information supporting environmental policies and other activities capable of affecting the environment. Rather than requiring the creation of one European database, INSPIRE built upon national and regional resources and specified requirements for metadata, discovery, viewing, downloading, interoperability and the sharing of information. For Czech institutions, implementation became a prolonged process of identifying relevant datasets, documenting responsibilities and aligning services with European specifications. The directive did not abolish national definitions or specialist needs. It created a common language through which information maintained in different countries and administrative systems could be discovered and, where appropriate, used together.

INSPIRE had particular significance because it transformed interoperability from a voluntary ideal into an obligation embedded in governance. Data providers were required to think about metadata completeness, access conditions, thematic specifications and service performance as part of their ordinary responsibilities. This encouraged a distinction between making a map visible and providing reusable information. A web image may support inspection, while a download service permits analysis of the underlying spatial objects and attributes. The difference matters for reproducibility. A researcher who cannot obtain or reliably identify the data behind a displayed map may be unable to repeat an overlay, test a hypothesis or review the consequences of a changed classification. The expansion of services therefore altered not only public convenience but also the conditions under which geographical findings could be independently examined.

Metadata became the practical instrument through which this new infrastructure could operate. A useful catalogue record identifies the responsible institution, geographic extent, subject, temporal validity, coordinate system, data quality, update frequency and conditions of access. It may also describe the lineage of a layer, explaining whether its geometry originated in field surveys, remote sensing, older maps or administrative transactions. These details allow users to decide whether the dataset is suitable before investing in processing. They also protect institutional memory when staff, software or project funding changes. The development of metadata catalogues at the Czech Geological Survey, in environmental administration and across national geospatial services gradually reduced dependence on informal professional contacts. The ability to find a dataset through a documented public interface represented a significant change in the social organisation of geographical knowledge.

Standardised network services addressed a complementary problem: how to use information without transferring every complete dataset into a separate local system. Services following the specifications of the Open Geospatial Consortium, including Web Map Service and Web Feature Service, supported the exchange of rendered map layers and structured geographic features respectively. Catalogue interfaces, downloadable packages and later web-oriented application interfaces served related but distinct purposes. This technological diversity was not simply a proliferation of abbreviations. It reflected different relationships between provider and user, ranging from the occasional consultation of a background layer to automated processing of detailed records. Czech institutions had to balance compatibility with established geographic software, the costs of hosting services and changes in international

standards. Their work also showed that technical compliance was only the beginning: well-described fields, understandable error messages and a reliable update policy remained essential for genuine reuse.

The national INSPIRE geoportal offered a particularly visible example of federated information. Managed through CENIA, it connected records and services from central ministries, regional authorities, local administrations, scientific organisations and other producers. It functioned as a point of discovery rather than proof that all participating information had been homogenised. For a researcher examining landscape transformation, the ability to locate topography, land-cover data, environmental restrictions and administrative boundaries through related catalogue entries greatly simplified the initial search. The next stages still demanded professional judgement about scale, historical correspondence and analytical definitions. The portal thus made differences between sources more manageable without making them disappear. In this respect the infrastructure supported a more transparent kind of scientific work, in which the provenance and institutional context of evidence could remain visible throughout analysis.

National strategic coordination developed alongside these service networks. In October 2014 the Czech government approved a strategy for developing infrastructure for spatial information to 2020, commonly known as GeoInfoStrategie. It addressed the problem of fragmented competencies by proposing a more coherent direction for the creation, maintenance and sharing of spatial information within public administration. In November 2021 a successor, GeoInfoStrategie 2020+, was approved with a planning horizon extending to 2027. These initiatives were not themselves scientific discoveries, and their effects cannot be inferred merely from the publication of policy documents. Their historical importance was the formal recognition of spatial information as a resource requiring sustained national coordination, education, interoperable public services and cooperation with research and innovation. They situated geographically referenced evidence within the broader modernisation of Czech e-government.

The development of national coordination also exposed the limitations of centralisation. Ministries hold data under different statutory mandates, and municipalities generate detailed information that may be absent from national collections. Universities require access for exploratory research, while emergency services and infrastructure managers demand reliable operational updates. A single institution could neither collect all such information competently nor define every appropriate use. The emerging Czech model therefore depended on distributed custodianship within increasingly common legal and technical arrangements. This approach could preserve expertise but required negotiation over funding, quality assurance, data exchange and responsibility when conflicting records appeared. The resulting infrastructure was better understood as an organised set of relationships than as one map or one database. Its effectiveness depended upon the willingness and capacity of institutions to maintain those relationships over time.

A major change in the accessibility of spatial information occurred as open-data principles acquired legal and practical force. The Czech surveying administration began providing designated open spatial datasets and their metadata without charge under the Creative

Commons Attribution 4.0 licence from 1 January 2020. From 1 July 2023 the Land Survey Office further extended free open-data provision to such fundamental resources as ZABAGED, national orthophotography, state map products, geographic names and survey control information. These were important milestones for academic research because they reduced the transactional costs of acquiring consistent reference data. A doctoral student, small research team or regional institution no longer had to treat access to certain national layers as a major budgetary decision. Attribution and documentation obligations remained, but the principle of reuse had become substantially more permissive.

Open access did not, however, make every geographical observation equally public. Certain historical archives, source aerial photographs, personal information, sensitive biological records and data held under specialised conditions remained subject to restrictions. Moreover, the possibility of downloading a file did not guarantee that its content could be interpreted correctly or combined without loss. Different licences, data models and definitions could still prevent seamless aggregation. An open-data policy therefore had to be accompanied by understandable metadata, predictable identifiers and stable services. The distinction between public visibility, free access, legally authorised reuse and substantive interoperability was one of the most important lessons of this period. Each step removed a different obstacle, and none automatically produced the others. This was particularly relevant to scientific datasets whose limitations were not obvious to users encountering them through a general-purpose portal.

European open-data policy reinforced the national shift. The 2019 directive on open data and the reuse of public-sector information placed greater emphasis on accessible public information, while Commission Implementing Regulation 2023/138 specified high-value datasets and arrangements for their publication. Geospatial information, Earth observation and environmental data, meteorological information, statistics and mobility data appeared among the relevant categories. Requirements for machine-readable publication, suitable application interfaces and, where specified, bulk downloads supported uses beyond the viewing of static maps. For Czech geographers, this regulatory development widened the expected audience for national data to include cross-border research collaborations, software developers and public-interest organisations. Yet the regulations also made questions of privacy, licensing, service capacity and precise data descriptions more salient. Greater availability increased the need for responsible stewardship rather than diminishing it.

The construction of the Digital Map of Public Administration, DMVS, and the regional digital technical maps demonstrated how these principles entered a more demanding operational field. Legal and organisational preparations intensified after amendments to surveying legislation in 2020, and the central information system entered production in July 2023. Regional digital technical map systems subsequently reached production operation on 1 July 2024. Their purpose differed from that of a general topographic map: the emphasis fell on detailed spatial information concerning technical and transport infrastructure and on the relationships among owners, operators and public authorities. For scientific research, such systems offered the prospect of more consistent evidence about the built environment, while also raising questions about coverage, access permissions and the interpretation of utility

records. The project exemplified the increasing convergence of geographic data governance with the practical management of infrastructure networks.

The significance of the digital technical maps was not confined to precision of representation. An underground utility, unlike a visible building, cannot usually be verified from ordinary aerial photography, and its record may pass through several organisations during planning, construction, maintenance and alteration. The technical map therefore depends on agreed updating responsibilities and on the distinction between surveyed reality, supplied records and information whose completeness cannot be assumed. This concern bears directly upon scientific applications involving urban exposure, flood vulnerability, heat networks or infrastructure resilience. Researchers need to establish not only where a line is drawn but whether the data describe a current installation, a proposed object or a historical record. The DMVS experience underscored a broader principle: authoritative geospatial infrastructure is sustained by institutions that can correct and account for information, not merely by high geometric resolution.

The Czech Geological Survey developed one of the most substantial thematic infrastructures within this broader environment. Its Geological Information System, GeoIS, organised databases describing geological mapping, boreholes, mineral resources, geohazards, documentary archives and other evidence accumulated through research and professional investigation. The agency's central data holdings brought together material with very different temporal and technical origins. Nationwide vector geological mapping at 1:50,000, e.g., required the reconciliation of adjoining sheets, unified legends and geometry adjusted to common bases. More detailed digital mapping at 1:25,000 developed from work undertaken since 1999, while other products supported national or regional synthesis. This form of integration was not simply cartographic: it sought to make different episodes of geological investigation usable within a persistent, searchable information environment.

The digitisation of geological archives illustrated the temporal depth that an effective spatial infrastructure must accommodate. During 2000–2004, the Czech Geological Survey developed a digital map archive incorporating tens of thousands of published and unpublished geoscientific maps and related documentation. A historical manuscript may be difficult to classify within a modern data model, but it can preserve an observation made before quarrying, urban expansion or environmental disturbance altered a site. Scanning such material protects access to its content, while georeferencing and indexing help connect it to present-day locations. The archival image is not necessarily a modern observation with known positional accuracy. Its research value often rests on careful comparison with other sources and an understanding of the techniques and aims of its original creator. Digital preservation thus extended the usable temporal horizon of Czech Earth-science research.

The geological map services subsequently allowed users to move between relatively general national representations, detailed thematic datasets and the documentary traces from which interpretations had been assembled. Data concerning landslides, mining activity and subsurface exploration could be consulted alongside geological maps and planning-relevant information. The provision of web services and downloads according to INSPIRE specifications improved access for institutions without specialist geological database systems.

Nevertheless, a geological boundary remains an interpretation, not a directly observed line of the same type as a surveyed property boundary. Responsible spatial integration requires the preservation of that distinction. When geological units are overlaid with building inventories or groundwater observations, the precision of the graphic intersection must not be mistaken for equal certainty in all component datasets. The Czech geological infrastructure therefore provided both a technical model and an illustration of the limits of purely geometric interoperability.

Environmental monitoring made these problems particularly visible because it combined location with repeated observation through time. The Czech Hydrometeorological Institute maintained networks and national databases for weather, hydrology, air quality and related measurements, offering information essential to understanding processes that cross administrative boundaries. A station's coordinates identify the point of measurement, but the time series also depends upon instrumentation, relocation history, observation frequency and procedures for quality control. Gridded products introduce additional assumptions through interpolation or modelling. Researchers joining such information to terrain, land cover or population data must distinguish station values from spatial estimates. This distinction became increasingly important as public portals made maps of meteorological and hydrological conditions appear immediate and comprehensive. The underlying networks remained expensive, carefully maintained scientific systems rather than anonymous streams of georeferenced numbers.

By 2025 the accessibility of hydrometeorological observations had acquired a further institutional dimension. The Czech legislation on the public hydrometeorological service, effective from the beginning of that year, established a framework for a national database of hydrometeorological data and products. The resulting open-data provision strengthened the relationship between measurements undertaken for public service and datasets reused in independent research. The possibility of obtaining documented observations can improve studies of drought, flooding, climatic trends and air pollution, particularly when the researcher needs to test a result against primary material rather than an illustrative map. Such openness does not remove the need to verify whether an observation is provisional, quality controlled, homogenised or derived. The scientific value of access depends on these distinctions being preserved and on the continued financing of the instruments, staff and processing systems from which the information originates.

The Nature Conservation Agency of the Czech Republic contributed a further kind of geographic evidence through its Information System for Nature Conservation, ISOP. Species records, protected-area information, habitat data and other conservation resources have relationships to places that cannot always be represented adequately by ordinary map layers. An organism may be observed at a precise point, a species may occupy an uncertain area and a protected territory may have a legally defined boundary. The agency's provision of databases, map services and downloadable resources helped make these forms of evidence usable in research and public decision-making. At the same time, controlled access and aggregation for sensitive records demonstrated that the widest possible publicity is not invariably the most responsible policy. For biodiversity research, data quality encompasses survey effort,

taxonomic consistency and the protection of vulnerable species as well as positional accuracy.

The Czech Statistical Office developed a complementary route towards integration by joining statistical reporting to territorial reference information. Population and housing censuses, registers of census districts and buildings, demographic series and commuting data acquire additional analytical power when the geography of their collection can be inspected and related to other datasets. The Statistical Geoportal, publicly launched in Czech in 2023 and subsequently offered in English, made interactive exploration of the 2021 Census more accessible to domestic and international users. In 2025 the office expanded this environment through an open GIS data portal, initially operating in pilot form from January to April and then providing a broader range of geographical and statistical datasets. This transition enabled researchers to obtain spatial data for their own processing rather than relying solely on predefined statistical maps. It strengthened the practical connection between human geography, territorial statistics and geoinformatics.

Statistical integration nevertheless demanded more than attaching numerical values to polygons. Confidentiality rules, the spatial scale of aggregation and changes in statistical units constrain what can legitimately be inferred from published information. A census district does not necessarily correspond to a socially coherent neighbourhood, and an average attached to an administrative unit does not describe every household within it. These are longstanding questions of ecological inference, sharpened by the apparent detail of digital mapping. Open geographic files can facilitate sophisticated spatial statistics while also making misleading comparisons easier to produce. Good research practice consequently requires a clear account of the population represented, the reference date, the geometry of reporting units and the effect of aggregating or disaggregating observations. The Czech statistical geoportal widened access to evidence, but it did not replace the methodological responsibility of those analysing territorial inequalities.

European land-cover datasets offered another form of integration across institutional boundaries. CORINE Land Cover, developed within European environmental information programmes and subsequently distributed through the Copernicus Land Monitoring Service, supplied comparable thematic inventories for reference years including 1990, 2000, 2006, 2012 and 2018. Czech researchers could place national patterns of landscape transformation within a wider continental frame without first devising an entirely separate classification for each neighbouring country. The programme’s thematic categories and minimum mapping units, however, also required careful interpretation. CORINE was designed for consistent regional assessment, not for identifying every small patch of land use or recording the legal status of individual parcels. Its historical importance to Czech geoinformatics lay in demonstrating the analytical advantages, and inherent compromises, of a common multinational information product.

Integration between CORINE, national orthophotography, cadastral information and ecological field surveys made it possible to investigate landscape change at several scales. The data did not always agree, nor should they have been expected to agree. Land cover refers to observable physical characteristics, land use to human activities and legal classifications

to an additional institutional dimension. A forest cut and replanted between reference dates could appear differently in each source without any one dataset necessarily being defective. Furthermore, comparing change layers with independently classified status layers may require attention to their different minimum mapping units and production procedures. A mature geospatial infrastructure therefore makes disagreement analysable. It provides enough documentation for investigators to decide whether a difference indicates actual transformation, varying definitions, different observation dates or processing artefacts, instead of concealing these possibilities beneath a visually seamless composite map.

Alongside public administrative systems, the Czech scientific community created distributed observational infrastructures whose datasets could be linked to international research. CzechGeo/EPOS brought together geophysical observatories, permanent and temporary measurement stations, and related geological and geophysical databases. Its research infrastructure received national support through projects covering 2010–2015 and 2016–2019, with further modernisation undertaken through CzechGeo/EPOS-Sci during 2017–2020. The participating institutes of the Czech Academy of Sciences, universities, geodetic researchers and the Czech Geological Survey represented different specialisms united by a dependence on precise locations and comparable observations. Seismic, GNSS, geomagnetic, gravimetric and geodynamic data could be related through shared services and coordinated research programmes. This was an example of infrastructure organised around measurement and scientific exchange rather than around a conventional national map product.

The CzechGeo model revealed the importance of connecting local field measurements to broader scientific networks. Permanent observations acquire much of their interpretative value when compared over large territories and long periods; temporary deployments help test questions arising from regional anomalies or particular events. Integration with the European Plate Observing System and international data centres encouraged common descriptions of instruments, stations, time series and data-processing procedures. Yet disciplinary expertise remained indispensable. A signal recorded by a seismometer and a displacement inferred from satellite positioning cannot be merged merely because both have coordinates and timestamps. Their uncertainties, physical meanings and sampling characteristics must be understood before they can support a common interpretation of crustal processes. The infrastructure’s contribution to geographical research was therefore twofold: more accessible observation and more explicit cooperation over the meaning of scientific data.

Long-term ecosystem observations gave similar lessons in a different field. The Czech network associated with Long-Term Ecological Research linked sites where biological and environmental variables had been observed over extended periods. Such research is especially relevant to gradual changes in forests, wetlands and human-influenced landscapes that short projects may fail to detect. The internationalisation of long-term ecological research and its relationship to the developing European eLTER infrastructure encouraged attention to comparable site descriptions, data continuity and shared scientific protocols. CzechGlobe, the Global Change Research Institute of the Czech Academy of Sciences, meanwhile participated in European greenhouse-gas observation through the Integrated Carbon Observation System, linking atmospheric and ecosystem measurements. These resources

supplied spatially anchored evidence at temporal resolutions and observational scales distinct from those of national mapping, while helping to connect Czech research to wider investigations of environmental change.

Universities and research organisations were not merely consumers of these infrastructures. Departments of geography, geoinformatics, geomatics, geology and environmental sciences contributed methods for integrating heterogeneous information, assessing uncertainty, modelling spatial relationships and presenting results to different audiences. Teaching laboratories and research projects also provided a setting in which students learned to work with official services, satellite-derived products and field measurements in the same analytical workflow. The growth of open-source geographical software and reproducible scripting widened the range of institutions able to undertake such work, although access to computing skills and reliable technical support remained uneven. Educational capacity was itself a component of infrastructure: without people who could examine metadata, transform coordinate systems and evaluate source quality, the proliferation of accessible datasets would not necessarily lead to better geographical science.

Scientific data management gradually required greater attention to principles commonly summarised as findability, accessibility, interoperability and reusability. These qualities are related but not interchangeable. A dataset may be easily found yet restricted for legitimate reasons; freely downloadable information may be unusable without a codebook; technically compatible layers may remain scientifically incomparable. Persistent identifiers, recorded processing histories, clear licensing and publication of methods can make complex research outputs more durable. For datasets containing continuous observation, versioning and access to historical states are especially important, because a continually updated service may no longer display precisely the information used in an earlier publication. Czech research institutions increasingly operated within international expectations of accountable data stewardship, but implementation remained dependent on discipline, resources and institutional practice rather than following a single uniform model.

The limits of integration were most evident where geography, time and governance intersected. Administrative boundaries change; sensors are replaced; classification schemes evolve; records are corrected after publication; and an apparently authoritative dataset may be unsuitable at a finer scale than that for which it was produced. Cross-border research adds differences in national law, mapping traditions and availability of historical observations. Data protection imposes further necessary constraints, particularly where precise addresses could be connected with individual-level information. These problems cannot be solved by placing everything in one repository. They require documented decisions about aggregation, transformation, uncertainty, access and responsibility. By the middle of the 2020s the Czech experience suggested that the most valuable infrastructure was not the one concealing all discrepancies, but the one enabling researchers to recognise them, assess their significance and justify the methods used to address them.

By 2025 the Czech Republic possessed a far more interconnected geospatial information environment than had existed at independence. National reference layers, registers, scientific observatories, environmental databases, statistical services and European portals could

support investigations that once demanded extensive individual data acquisition and conversion. Progress had been uneven and the maintenance of services remained a continuing obligation rather than a completed task. Nevertheless, the combination of institutional continuity, regulatory harmonisation, open-data reforms and distributed scientific cooperation changed what geographical research could reasonably attempt. A question concerning flood exposure, settlement change, geological hazards or ecosystem transformation could now draw upon several recognised sources while retaining a clearer account of their origin and limitations. The enduring achievement was the establishment of geospatial information as shared scientific infrastructure: a maintained, revisable and critically interpretable basis for research across disciplines and borders.

Major Achievements, Research Schools, Leading Scholars and Landmark Publications in Cartography and Geoinformatics

The history of Czech cartography and geoinformatics between 1993 and 2025 is best understood as the transformation of an established mapping culture into a diversified field of scientific enquiry. The foundation of the independent Czech Republic did not create cartographic knowledge anew: survey organisations, university departments, topographic map series, geographical journals and extensive collections of historical documents already existed. What changed was the manner in which these resources were organised, questioned and connected. Digital data became an object of methodological research rather than merely a faster means of drawing maps, while visual representation developed into an experimentally investigated interface between geographical evidence and human judgement. The principal achievements of the period therefore include not only recognised atlases and reliable reference databases but also new schools of GIS analysis, cognitive cartography, historical geoinformatics, remote sensing and applied spatial modelling. Their significance lies in the capacity to make different kinds of spatial knowledge comparable without erasing the disciplinary assumptions on which each depends.

The first years after 1993 combined continuity with considerable institutional uncertainty. Formerly centralised practices in surveying, state mapping and data distribution had to be adapted to the requirements of a smaller sovereign state, a market economy and a restructured system of higher education. Public agencies retained responsibility for authoritative geographic frameworks, while private firms increasingly supplied mapping software, services, printed products and digital applications. Universities acquired greater scope to establish specialist curricula and pursue international research partnerships. These developments did not proceed at the same rate. Some cartographic research groups moved rapidly towards computer-based terrain modelling and GIS, whereas other institutions first concentrated on maintaining the accuracy of national reference information. The resulting plurality proved productive: academic researchers could test new approaches against operational geographical datasets, and public authorities could evaluate innovations whose usefulness had been demonstrated in scientific and educational work. The Czech experience

thus resists a simple narrative in which analogue cartography was replaced by a single unified digital technology.

An essential scientific achievement was the consolidation of a distributed research community with identifiable centres rather than one dominant national school. Brno developed a strong tradition of cartographic theory, dynamic visualisation and geoinformation for decision support; Olomouc became prominent in thematic atlas construction, user-centred design and geovisualisation; Ostrava established professional geoinformatics education and a sustained conference culture; Prague combined mathematical and applied cartography with historical map analysis and public map collections. Plzeň, through geomatics education, contributed to the continuing interaction between surveying, spatial data processing and engineering applications. These specialisations overlapped, especially where scholars moved between universities, supervised doctoral students or collaborated on atlas projects. Their value was not territorial exclusivity but the existence of several intellectual environments capable of questioning one another's methods. By the 2010s the field was recognisably interdisciplinary, with connections to climatology, urban planning, heritage studies, environmental management, psychology and computer science.

The Laboratory on Geoinformatics and Cartography at Masaryk University in Brno illustrates how a research school could emerge during the transition itself. Established in 1992 under the leadership of Milan Konečný, it entered the independent Czech period already prepared to combine traditional geographical and cartographic expertise with the expanding possibilities of GIS. Its research programme treated a map as a structured representation whose contents and appearance should respond to a specific analytical problem. Work on dynamic mapping, geovisualisation and support for crisis management connected geographical modelling with questions of interface design, changing information needs and public decision-making. The laboratory's contribution was consequently broader than software adoption: it helped construct a vocabulary for asking when a map is useful, what information its user must receive, and how that information ought to change as a situation develops. The Brno school also cultivated collaboration across national boundaries, providing a visible Czech contribution to international debates on the social responsibility of cartography.

Milan Konečný's scientific and organisational career symbolises this international orientation. His leadership of the Brno laboratory coincided with participation in European geoinformation initiatives and efforts to connect digital cartography with disaster prevention and early warning. His election as president of the International Cartographic Association for 2003–2007 followed earlier service as vice-president and gave the Czech research community a prominent position in the discipline's global institutions. This achievement should not be mistaken for evidence that Czech approaches simply became universally accepted. Rather, it created opportunities to introduce Central European research problems, including flood management and public-sector data coordination, into larger comparative discussions. Konečný's emphasis on geoinformation as a component of an information society also anticipated the increasingly demanding task of integrating reliable spatial data with social, administrative and environmental information. His influence was exercised through research, supervision, scientific networking and the construction of durable academic partnerships.

A particularly characteristic contribution from Brno concerned adaptive and context-sensitive cartography. Instead of assuming that a single visualisation could serve all purposes, researchers distinguished the informational requirements of prevention, preparedness, emergency response and recovery. In the case of flooding, e.g., a long-range risk assessment may need information on catchments, land cover and exposure, while an operational response map must emphasise current accessibility, vulnerable locations and the changing spatial distribution of danger. Research associated with Petr Kubíček, Eva Mulíčková, Milan Konečný and their collaborators explored how these requirements could be expressed in geoinformation systems and cartographic designs. The 2011 study on flood management and geoinformation support within the emergency cycle is a clear bibliographical marker of this programme. Its wider importance is conceptual: the map is treated neither as a decorative illustration of expert conclusions nor as a neutral database display, but as a carefully designed element in a sequence of decisions made under different conditions of uncertainty.

Further Brno work widened the question of cartographic effectiveness from operational relevance to perception and cognition. Researchers including Zdeněk Stachoň, Petr Kubíček, Lukáš Herman and Čeněk Šašinka investigated aspects of map reading, symbol recognition, spatial orientation and 3D geovisualisation. Experimental procedures, especially observation of visual attention and controlled comparisons between cartographic alternatives, created an empirical basis for assessing designs once justified chiefly through professional convention. Research into the interpretability of interactive scenes also brought cartographers into contact with psychologists and human-computer interaction specialists. This did not eliminate aesthetic judgement or the traditional rules of cartographic composition. It made those rules open to testing, refinement and discussion in relation to a defined population of users. In methodological terms, such investigations helped reposition cartography as a science of geographical communication in which the behaviour of the map reader forms part of the evidence.

The establishment of specialist geoinformatics education at VSB–Technical University of Ostrava represented another early landmark. Petr Rapant's initiative led to an accredited study programme in geographical information systems in 1994, at a time when the subject was still often taught as a set of techniques within geography, surveying or computing. The Ostrava approach made the integration of databases, algorithms, geographical modelling, cartography and practical application a recognisable professional field. Its intellectual consequences extended beyond the university's graduates. The need to teach the subject systematically encouraged textbook production, terminological clarification and explicit discussion of how spatial information differs from ordinary tabular data. The GIS Ostrava symposium, organised from 1994, provided a long-running meeting place for researchers, public agencies, commercial specialists and students. This continuity was especially valuable in a discipline whose technical systems changed rapidly and in which a shared professional language had to be continually reconstructed.

The Ostrava conference tradition also documents the expansion of the subjects regarded as legitimate geoinformatics research. Early professional discussion was closely associated with data conversion, GIS architecture, municipal applications and the transfer of technical

experience. Over time the programme accommodated spatial statistics, transport modelling, remote sensing, mobile positioning, geovisualisation, open data, distributed services and increasingly automated forms of analysis. Proceedings published from 2014 within Springer's Lecture Notes in Geoinformation and Cartography series made selected contributions more visible internationally. The significance of such a forum cannot be measured solely by citation counts. It sustained contact between university methods and the practical limitations of incomplete datasets, inconsistent standards, software constraints and changing administrative needs. Alongside it, the student-oriented GISáček meetings, begun in 1998, supported scholarly continuity by bringing early-career researchers into contact with a broader professional community. These events constituted an infrastructure of exchange as real, although less visible, as a national geographic database.

Olomouc developed a complementary intellectual identity through the work of Vít Voženílek and the Department of Geoinformatics at Palacký University. Geoinformatics teaching expanded from the late 1990s, and Voženílek subsequently headed the department from 2001 to 2022. His research and publications addressed GIS education, terrain modelling, thematic cartography, atlas methodology and the communication of geographical information. Works such as Geografické informační systémy I, published in 2000, helped equip Czech students with a coherent framework for understanding the relationship between data structures, analytical operations and cartographic output. The department's importance, however, cannot be reduced to one textbook or one scholar. It developed a sustained capacity to organise collective atlas projects, investigate the cognitive reception of maps and link scientific representation with questions of design, accessibility and professional ethics. Its graduates and collaborators contributed to research extending beyond the region, making Olomouc a recognisable centre of Czech geoinformatics.

Voženílek's involvement in the International Cartographic Association, including service as vice-president during 2015–2023, reinforced the Olomouc school's international connections. The department's work demonstrates how thematic cartography can combine disciplinary expertise with advanced visual communication without dissolving into generic information design. Scientific atlases produced by its researchers required the reconciliation of different measurement scales, regional classifications, observation periods and traditions of thematic notation. Their construction was therefore an exercise in conceptual integration as well as graphical composition. The most persuasive atlas maps were those in which spatial relationships could be inspected while important differences in the meaning of underlying datasets remained intelligible. Research on atlas design also created a bridge between the established national tradition of synthetic cartographic works and a newer culture of interactive, specialised and occasionally experimental mapping. This continuity explains why atlas production remained central to Czech cartographic scholarship even after maps could be generated routinely from GIS software.

One of the clearest collective achievements was Atlas podnebí Česka, published in 2007 through cooperation between Palacký University and the Czech Hydrometeorological Institute. Associated with editors and authors including Radim Tolasz, Tereza Míková, Alexandra Valeriánová and Vít Voženílek, the atlas brought together climatological observations and

cartographic methods to describe the country's climate in its geographical complexity. Its significance extended beyond the presentation of familiar distributions of temperature and precipitation. The work required decisions about temporal reference periods, spatial interpolation, topographic effects, thematic classification and the visual comparability of climatic characteristics. As a result, it demonstrated the value of cartographic synthesis in a science increasingly dependent on numerical models and geographically distributed measurements. The atlas also provided a durable reference point for geographical education and environmental interpretation at a moment when questions of climatic variability and change were gaining public and scientific prominence.

The 2012 Atlas fenologických poměrů Česka extended the same synthetic approach to the seasonal behaviour of plants and related environmental observations. Prepared by a multidisciplinary group including Lenka Hájková, Vít Voženílek, Radim Tolasz and Alena Vondráková, it translated dispersed records of biological timing into a structured account of geographical differentiation. Its cartographic significance lay in the challenge of representing events that are temporal as well as spatial: a mapped boundary between typical flowering dates, for instance, is not equivalent to a geological contact or an administrative line. Effective representation must communicate statistical variation, observation density and the limits of generalisation. Placed beside the climate atlas, the phenological atlas illustrates the movement from descriptive thematic maps towards products in which different scientific observation systems are interpreted together. Both works show that a major atlas can be understood as a research instrument whose methodological decisions remain relevant long after its initial publication.

The Landscape Atlas of the Czech Republic, issued in 2009 under the auspices of the Ministry of the Environment and the Silva Tarouca Research Institute for Landscape and Ornamental Gardening, occupies a distinctive place among national cartographic works. Published bilingually as Atlas krajiny České republiky / Landscape Atlas of the Czech Republic, it assembled a large body of maps and accompanying material covering the historical, physical, ecological, cultural and socioeconomic dimensions of the Czech landscape. Its scale of production was itself noteworthy: the volume extended to more than three hundred pages and drew on contributions from numerous research and professional organisations. Yet its defining achievement was the attempt to represent landscape as an interconnected scientific subject rather than a collection of separate environmental indicators. Historical land use, settlement, natural systems and contemporary pressures could be considered within a common cartographic framework. The atlas consequently belongs both to the history of Czech cartography and to the wider intellectual effort to reconcile physical and human geography.

The landscape atlas also highlighted the particular difficulties of large collaborative publications. The spatial units appropriate to geomorphology, settlement structure, biodiversity and landscape planning are not interchangeable, and maps created from different source materials inevitably vary in positional accuracy, resolution and chronology. Editorial coordination was therefore inseparable from scientific judgement. The atlas's analytical and synthetic maps encouraged readers to explore associations between the geographical inheritance of a territory and its present organisation. Its recognition at the international

cartographic level, including an award in the national and regional atlas category at the 2011 International Cartographic Conference in Paris, demonstrated the visibility attainable by Czech atlas production. That recognition should be interpreted in relation to the quality of the final communication as well as the volume of underlying information. The work showed that a printed national atlas could remain intellectually ambitious at the beginning of the digital age precisely because its contents had been selected, integrated and critically designed.

Not all significant atlas achievements possessed the breadth of a national landscape synthesis. Smaller specialist works often offered more explicit experimentation with audience, scale and subject. The 2013 atlas of special educational counselling centres prepared by Voženílek, Jiří Michalík, Alžběta Brychtová and Alena Vondráková demonstrated how a geographical representation could make the distribution of specialised public services intelligible to decision-makers and users. Subsequent mapping of Czech dialects, including the 2020 atlas devoted to vowel shortening and related studies of linguistic geography, connected cartographic methodology with language variation. These projects enlarged the conventional boundaries of thematic cartography: the phenomena represented were neither purely physical nor simply economic, and the spatial categories often required careful interpretation. Their achievement was to show how an atlas could open specialised scholarly evidence to wider examination while retaining the subject's own conceptual vocabulary. Maps functioned as comparative arguments, not merely as illustrations placed beside an independent text.

The Olomouc school also became influential through research into how maps are actually perceived. Stanislav Popelka, together with collaborators including Alžběta Brychtová, Alena Vondráková and Jan Brus, helped establish eye-tracking as a practical method of cognitive cartography. Experiments made it possible to observe sequences of visual attention while participants read two-dimensional maps, examine terrain representations or interact with 3D scenes. Publications such as Popelka and Brychtová's 2013 study of the perception of two- and 3D terrain visualisation helped convert a familiar cartographic argument into a testable question. Did adding depth improve understanding, or did it create distractions? Could relief shading facilitate interpretation while making some labels harder to locate? Rather than presupposing an answer, the experiments related characteristics of the display to the tasks performed by its readers. This was a substantial methodological advance for a discipline whose design principles had long depended on accumulated expert experience.

Popelka's later publications, including the 2015 monograph on evaluating 3D GIS visualisations through eye-movement recording and the 2018 practical guide to eye-tracking in cognitive cartography, consolidated the experimental approach. They helped make research procedures reproducible by addressing the formulation of tasks, selection of participants, recording conditions and interpretation of visual attention. Such work requires caution: looking at a map feature does not automatically imply understanding it, while the performance of a particular user group cannot be generalised to all contexts. Nevertheless, eye-tracking provides evidence that can complement interviews, performance measures and assessments of map literacy. Its emergence in Czech geoinformatics strengthened the relationship between cartographic theory and the experimental study of human behaviour. It also encouraged

collaboration with institutions outside geography, particularly where the interpretation of complex visual scenes demanded expertise in psychology, statistics and interaction design.

Alena Vondráková contributed another dimension to the modernisation of cartographic research by examining thematic and atlas design together with copyright and other non-technological conditions of map production. Her work illustrates that the apparent ease of creating digital maps can conceal important issues of intellectual ownership, attribution, data reuse and professional responsibility. Publications such as Autorské právo v kartografii a geoinformatice, issued in 2012, and Netechnologické aspekty mapové tvorby, published in 2014, argued in practice for attending to the legal and communicative environment of cartographic work rather than judging output solely by technical sophistication. These concerns became more consequential as maps were published online, assembled from multiple providers and reused beyond the circumstances of their creation. In scientific terms, attention to the provenance and permissible use of information also supports reproducibility: a map whose sources cannot be traced or whose data cannot lawfully be examined is limited as a research product, however polished its design.

Jaroslav Burian and colleagues in Olomouc advanced the application of GIS to urban development and spatial planning. Their research examined changes in functional land use, the representation of planning information and the consequences of alternative spatial arrangements. The 2013 article on the development of Olomouc from 1930 to 2009, written with Jan Brus and Vít Voženílek, illustrates the productive connection between cartographic reconstruction and contemporary urban analysis. Its temporal scope crossed several political and economic systems, allowing changes in the city's functional areas to be compared within a mapped framework. The 2015 study of Urban Planner, prepared with collaborators including S. Šťastný, Brus, Vilém Pechanec and Voženílek, extended this approach to scenario modelling. Instead of treating a planning map as the final record of a decision, such work treated spatial information as material for evaluating possible futures. It made cartography an active participant in the analytical process through which planning alternatives are constructed and tested.

The importance of applied urban geoinformatics lies partly in its capacity to reveal uncertainty and disagreement. A model can estimate the attractiveness of locations, the accessibility of services or potential conflicts between development and environmental protection, but its results depend on the assumptions encoded in criteria and weights. Czech work on spatial planning therefore provided opportunities to discuss the limits of automated decision support. Land suitability is not an objective property existing independently of social priorities, and a technically precise map cannot decide which interests should prevail. Research into the presentation of planning information made this problem visible, especially when symbols had different meanings across local administrations or when complex output was communicated to non-specialists. In this respect, the methodological achievement was twofold: spatial analysis became more powerful, while scholars became better equipped to explain why its outputs required expert and democratic interpretation.

Prague's contribution to historical cartography emerged from an unusually rich conjunction of archives, map collections, historical scholarship and engineering-oriented geoinformatics.

The Historical Institute of the Czech Academy of Sciences sustained a tradition of historical-geographical work and atlas compilation, while the Faculty of Civil Engineering of the Czech Technical University in Prague developed methods for analysing, transforming and presenting historical maps. Eva Semotanová and Jiří Cajthaml became particularly visible representatives of this intellectual partnership. Historical mapping here was not understood as a simple exercise in decorating historical narratives with old images. Maps were critically examined as evidence produced under particular administrative, technical and political conditions. Their geographical content could be assessed for accuracy and change, while their historical context helped explain the intentions and constraints of the original compilers. The result was a productive dialogue between historical source criticism and the computational tools of modern cartography.

The series Historický atlas měst České republiky, published from 1995 under the Historical Institute's direction, illustrates the long-term value of this combined approach. Individual volumes bring together reproductions of historical maps, plans, views and photographs with reconstructed cartographic information and interpretative texts concerning particular Czech towns. The project follows principles associated with the wider European tradition of historical town atlases, making comparisons of urban form and development possible across national boundaries. Its achievement should not be confined to documenting the appearance of historic centres. The atlases illuminate how settlement, circulation, industry, political authority and landscape change became embedded in urban morphology over time. As the series expanded, digitisation and selected online applications offered additional ways of comparing documents. Yet the printed volumes remained important precisely because they subjected heterogeneous sources to editorial selection, documentation and historical explanation.

An especially influential landmark was Akademický atlas českých dějin, issued by Academia in 2014 and associated with Eva Semotanová, Jiří Cajthaml and a large interdisciplinary team. The atlas assembled cartographic, graphical and textual presentations of Czech and Czechoslovak history in its Central European and international setting. Its stated intellectual framework connected people, space and time, a formulation that made cartographic method central to historical interpretation rather than supplementary to it. The maps were not simply a sequence of changing political borders. They addressed demographic, economic, cultural, military and social phenomena whose geographical distributions reveal patterns not always evident in conventional narrative history. The atlas became a major example of cooperation between historians and specialists in geoinformation technology, bringing together source analysis, spatial modelling and carefully controlled thematic representation. Its distinction in the 2015 Magnesia Litera awards further indicated the ability of a scholarly atlas to reach a readership beyond the specialised community of cartographers.

The Akademický atlas was followed by further projects that transformed historical synthesis into a more openly accessible digital form. Český historický atlas: Kapitoly z dějin 20. století appeared in 2019, while the associated Czech Historical Atlas project, developed jointly by the Historical Institute and the Czech Technical University during 2016–2020, generated an online map portal and related resources. These outputs demonstrate an important difference

between the publication of a historical atlas and the creation of a reusable historical information environment. A printed map expresses a curated argument in a stable arrangement; a portal can permit users to switch subjects, examine different territories or explore links between source records and their cartographic interpretation. Neither is inherently superior. The scholarly challenge is to preserve documented interpretation while enabling new questions to be asked of the data. The Prague projects showed how the authority of historical research could be retained in an interactive setting without pretending that reconstructed boundaries or past distributions possessed the accuracy of modern geodetic measurements.

Jiří Cajthaml's work on the georeferencing, transformation and distribution of old maps exemplifies the technical foundation of this research. His doctoral dissertation in 2007 dealt with new technologies for processing and making historical maps accessible, while later work explored their spatial accuracy and analytical potential. Research with Jiří Krejčí on distributing old maps through web map services made a particularly instructive contribution: it demonstrated how historical materials could become interoperable layers in contemporary GIS rather than remaining isolated scanned images. This required choices about coordinate reference systems, geometric transformation, the treatment of map-sheet distortion and the documentation of uncertainty. Such decisions determine whether apparently precise overlay analysis is scientifically defensible. Cajthaml's research at the Czech Technical University helped turn historical cartography into a technologically active discipline without sacrificing attention to the original map as a constructed historical source. It also strengthened links between surveying sciences and the humanities.

A related achievement was the systematic digitisation and dissemination of historical map collections. The Map Collection of the Faculty of Science at Charles University and the geographical collections at Masaryk University became important centres for preserving, cataloguing and studying cartographic documents. The TEMAP initiative, involving university and library partners, created procedures for making valuable map holdings accessible through digital systems, while work associated with StareMapy.cz and OldMapsOnline supported spatial discovery and georeferencing. These developments were significant for scholarship because conventional catalogues often locate a map by title, maker or date, whereas historical researchers may need to find documents covering a particular territory. A geographic search interface can therefore change the questions that are practically answerable. At the same time, digitisation is not equivalent to complete intellectual access. Reproductions remain dependent on metadata quality, intellectual-property conditions and responsible interpretation of the source's date, coverage and accuracy.

The preservation of older maps also created new analytical possibilities in landscape history. Georeferenced cadastral plans, military surveys and successive topographic series can help reconstruct alterations in roads, wetlands, river courses, field boundaries, settlement patterns and woodland. These studies depend on distinguishing genuine landscape change from changes introduced by survey instruments, map projections, scales or drawing conventions. The work of Czech geoinformaticians helped normalise this distinction and introduced practical methods for assessing how far comparisons can be trusted. Historical map analysis

became relevant to archaeology, heritage protection, geomorphology and the study of environmental degradation. The institutional significance was equally important: a source once consulted mainly by historians could be interrogated in GIS by geographers, ecologists and urban planners. The methodological gain consisted not only of faster processing but also of a more explicit account of the uncertainties accompanying every attempt to translate past spatial representations into present-day coordinates.

The state mapping and cadastral system formed a parallel centre of cartographic achievement, although its outputs differed from those of university laboratories. The Czech Office for Surveying, Mapping and Cadastre and its specialised organisations maintained and improved the authoritative foundations on which much scientific analysis depends. ZABAGED, the Fundamental Base of Geographic Data, developed from the mid-1990s as a detailed national reference framework, while orthophotography, elevation models, digital cadastral information and territorial identifiers were progressively improved. Their scientific importance lay in enabling repeated analysis against sufficiently consistent geographic references. A reliable base map does not itself test a geographical hypothesis, but inconsistent roads, addresses, boundaries or terrain data can invalidate comparisons before a hypothesis is even examined. The achievement of state cartography was therefore cumulative and often unspectacular: maintenance, revision, positional accuracy and documentation made independent investigations more reliable. This must be distinguished from academic innovation without treating the two forms of work as unrelated.

The expansion of 3D spatial observation changed both the scope and the expectations of Czech geoinformatics. Airborne laser scanning, digital photogrammetry, satellite imagery and unmanned aerial vehicles enabled measurements of terrain, vegetation and built structures that could not be supplied by conventional planimetric maps alone. Czech research groups working at technical universities and in environmental sciences developed methods of image processing, surface reconstruction and 3D representation for practical investigation. Karel Pavelka's work in photogrammetry, particularly the documentation and visualisation of cultural heritage, exemplifies a trajectory in which spatial measurement became an instrument for conserving objects and places as well as mapping territory. Later studies integrating laser scanning and unmanned aerial observation demonstrated that heritage research could benefit from a combination of accurate geometry and interpretative visual models. Such work connects cartography with the production of inspectable scientific records of structures that may deteriorate or disappear.

The contribution of remote sensing to cartographic research was particularly evident in environmental monitoring. Satellite time series and aerial images supported work on forest condition, changes in agricultural land, urban expansion, drought effects and the consequences of extreme events. Research at Palacký University and other Czech institutions linked spatial analysis to ecosystem science and geographical planning, while national environmental agencies and European programmes supplied observations suitable for wider comparison. The major achievement was not the discovery that satellite images could be displayed as maps; that had long been established. It was the development of workflows in which radiometric information, classification models, ground observations, digital terrain data

and thematic cartography could be combined transparently. This also created new obligations. Maps based on automated classification may convey misleading certainty if validation data, temporal mismatches or class definitions are concealed. The most useful Czech contributions therefore joined computational technique to a concern for the meaning and reliability of the resulting geographical claims.

Spatial data infrastructure research provided another route to international scientific relevance. Czech scholars participated in the practical interpretation of European interoperability requirements, including those associated with the INSPIRE directive adopted in 2007. At Masaryk University, Tomáš Řezník's methodological work on transforming existing national metadata into INSPIRE-compatible structures illustrates how apparently administrative problems can demand serious conceptual and technical analysis. Interoperability involves more than making a file readable by different software: datasets must be described consistently, their spatial and temporal reference understood and the meaning of categories preserved. Scholars investigating standards, services and distributed geoinformation systems thus addressed a central condition of reproducible geographical science. The relationship between the Czech research community and European spatial data policy was reciprocal. European frameworks encouraged national coordination, while operational experience in Czech institutions exposed questions of feasibility, maintenance, documentation and data quality that standards alone could not resolve.

The Czech Statistical Office's Statistical Geoportal, developed in connection with the dissemination of results from the 2021 census and launched as a public visualisation environment in 2023, provides an instructive example of institutional cartographic innovation beyond a traditional map-producing agency. It made demographic and statistical information accessible through geographic interfaces and received an international Special Achievement in GIS award in 2023. The significance of this project is not primarily the award. It lies in the improvement of connections between statistical geography, cartographic presentation and public access to evidence about population and territory. It also raises methodological concerns familiar to academic geographers: administrative units vary enormously in population and area, choropleth shading can exaggerate differences and classification decisions can influence conclusions. The best statistical mapping makes those constraints understandable while preserving sufficient detail for specialists. Public geovisualisation in this sense became part of the shared intellectual environment in which Czech geographical research operated.

A research school's durability is also reflected in its publications and modes of training. Czech cartographic work circulated through Geografie, the journal of the Czech Geographical Society, and through Geodetický a kartografický obzor, a long-standing Czech–Slovak professional and scientific periodical that continued across the state division of 1993 and moved to exclusively electronic publication in 2013. International articles appeared in outlets such as The Cartographic Journal, Cartography and Geographic Information Science, Journal of Maps, International Journal of Digital Earth and ISPRS International Journal of Geo-Information. Conference volumes, methodological guides, monographs and university textbooks had different audiences but were jointly essential to the development of the field. Their historical

role cannot be understood through indexing status alone: a textbook may establish common terminology for generations, whereas a specialist article may change how a particular visualisation technique is evaluated. The coexistence of Czech-language and international publication routes was therefore an asset, provided scientific standards remained demanding in both.

Professional associations contributed another form of continuity. Following the division of Czechoslovakia, the independent Czech and Slovak cartographic societies emerged from the previous federal organisation in 1993, and shared conferences continued to sustain professional discussion. The Czech society adopted the name Česká kartografická společnost in 2015. Its conferences, exhibitions and Map of the Year competition encouraged attention to cartographic quality across scientific, educational, governmental and commercial products. Such activities helped protect a conception of the map as a crafted intellectual object in an age when software made routine production easy. They also allowed professional discussion to pass between cartographers trained in different traditions. Awards do not establish scientific originality by themselves, and conference participation should not be confused with demonstrated research achievement. Nevertheless, professional institutions helped keep questions of representation, education, cartographic ethics and public communication visible as the technological environment changed.

The achievements of the period also reveal limits that ought to remain part of the historical account. Rapid development of GIS software did not automatically produce comparable, well-documented or openly available data; a greater number of online maps did not guarantee clearer public understanding. The location of research strength in particular universities sometimes depended on a small group of senior scholars, and projects requiring continuous maintenance were exposed to the instability of grant cycles. Differences between commercial platforms and academic systems could restrict reproducibility, while the training required to interpret sophisticated models did not always accompany the spread of user-friendly interfaces. Cartographic experiments presented additional limitations where sample sizes, user expertise or laboratory conditions constrained generalisation. Recognising such problems does not diminish the substantial progress made between 1993 and 2025. It clarifies that the central scientific accomplishment was the creation of communities able to identify and address methodological weaknesses rather than merely to accumulate new technical capacities.

By 2025 Czech cartography and geoinformatics had become a mature and internationally connected constellation of research traditions. Brno's work on dynamic and crisis-oriented cartography, Olomouc's atlas scholarship and experimental geovisualisation, Ostrava's systematic geoinformatics training and professional exchange, and Prague's integration of historical scholarship with digital methods were distinctive but mutually reinforcing. The landscape, climate, phenological and historical atlases demonstrated the enduring value of carefully designed synthesis, while studies of cognitive responses, spatial planning, interoperability and digital observation expanded the discipline's methodological frontiers. Leading figures such as Milan Konečný, Vít Voženílek, Eva Semotanová, Jiří Cajthaml, Petr Rapant and their collaborators helped shape these developments through both publications

and institutions. The broader legacy was the transformation of maps from authoritative finished images into critically interpreted, revisable and shareable forms of geographical evidence. That legacy provides a fitting conclusion to the history of cartography and spatial observation technologies in the modern Czech Republic.

Conclusion

Geography and Earth Sciences in the Czech Republic, 1993–2025: Scientific Continuity, Methodological Change and International Cooperation

The development of geography and Earth sciences in the Czech Republic between 1993 and 2025 is a history of continuity subjected to persistent reinvention. The independent state inherited unusually rich traditions of regional description, geological surveying, climatic observation, hydrological measurement, cartography and geographical theory. Yet the conditions under which inherited knowledge could be maintained, criticised and employed changed profoundly. Political and economic restructuring, European integration, expanding computational capacity and the growing consequences of environmental change altered both the questions asked of the Czech territory and the means available to answer them. No single breakthrough or institutional reform captures this experience. It is better understood as an accumulation of interacting transformations: the preservation of long observational records; the renewal of university research schools; the gradual circulation of data beyond their originating institutions; and the closer examination of the relations between physical processes, economic development and social inequality. The history explored in this book therefore concerns more than the success of particular disciplines. It reveals how an entire national knowledge system learned to connect its inherited intellectual capital with new demands for evidence, prediction, public accountability and international comparability.

The year 1993 provides a clear political boundary but not a scientific point of origin. Many of the decisive resources of Czech geography preceded the establishment of the republic: the institutional foundations of the Czech Geological Survey, the university tradition centred on Prague's Albertov, meteorological and hydrological networks, national map collections and the regionally differentiated knowledge produced during Czechoslovakia's twentieth-century development. These resources had survived changes in political authority and research priorities, although their accessibility and interpretative use had often been restricted by administrative arrangements. Independence demanded that institutions define responsibilities for a sovereign territory while continuing forms of cooperation across the former federal border. It also coincided with broader post-socialist reforms that changed university governance, public finance, environmental administration and the organisation of economic activity. The principal scientific task was thus neither to reject the past nor simply to inherit it, but to decide which long-established capacities could support a more open and diversified research system.

A useful distinction runs throughout the period between continuity of evidence and change in explanation. Geological sections, weather series, streamflow records, land registers, historical maps and census materials remained valuable precisely because they covered periods before the political transition. Researchers could not reconstruct long-term environmental variability from observations beginning in 1993. At the same time, economic

restructuring, migration, cross-border exchange and the revival of local self-government called for new conceptual frameworks. A regional hierarchy described under central planning did not necessarily explain the distribution of investment, commuting or public services in an increasingly market-oriented economy. Similarly, a flood catalogue compiled for engineering purposes could become the basis for probabilistic hazard analysis, spatial vulnerability assessment or ecological restoration. The Czech contribution lay partly in this productive tension: older evidence was not scientifically obsolete, but the problems through which it was interpreted were changing.

The first post-independence decade was characterised by uneven reorganisation rather than a uniform movement towards international models. Departments and research institutes differed in their personnel, inherited equipment, access to finance and capacity to establish foreign partnerships. The transformation of the former Academy of Sciences system altered the institutional location of some geographical research, while universities expanded their possibilities for doctoral education and disciplinary specialisation. The Institute of Geonics of the Czech Academy of Sciences, established under that name in 1993, illustrates this process particularly well. Its environmental geography workplace in Brno provided a route through which knowledge formerly associated with academy geography could be developed within a new organisational structure. The continuity of a research community could therefore be preserved without maintaining every preceding institution in its former form. Such transformations were sometimes disruptive, yet they also encouraged the coexistence of field-based, theoretical, quantitative and interdisciplinary approaches.

A second phase became increasingly visible around the Czech Republic’s accession to the European Union in 2004. European participation was not an instantaneous methodological conversion: Czech researchers already possessed international contacts, and many collaborations predated membership. Nevertheless, membership strengthened the practical importance of shared legal frameworks, cross-border research programmes, comparable statistical classifications and environmental reporting obligations. Regional development ceased to be interpreted only in relation to domestic administrative reform; it became connected with cohesion policy, European labour mobility and the restructuring of production networks. Water and environmental research acquired additional obligations to assess river basins and ecological conditions within common policy structures. Cartographic and geological information became more valuable when it could be combined with evidence produced in other countries. Consequently, Europeanisation operated simultaneously as an opportunity for research funding, a source of methodological discipline and a demand for institutional coordination.

After approximately 2014, and with particular intensity during the following decade, a further change occurred in the scale and accessibility of observation. Satellite imagery, airborne laser scanning, unmanned aerial systems, high-frequency sensors and web-based geographical information services became increasingly integral to everyday research practice. The expansion was not merely technological. It changed expectations concerning reproducibility, the speed of analysis, the geographical coverage of investigation and the communication of scientific results. Researchers could revisit a catchment after an extreme event using detailed

terrain data, compare settlement growth with historical cadastral evidence or connect national geological maps with European infrastructures. They could also encounter new problems: incompatible classifications, opaque analytical procedures, uneven access to specialist equipment, the uncertain future of data repositories and the temptation to regard visual precision as equivalent to scientific certainty. Digital transformation was therefore both an extraordinary enlargement of research capacity and a continuing test of methodological judgement.

Across these successive phases the Czech research system retained a distinctive institutional plurality. Public agencies, universities, academy institutes, professional societies, museums, archives, regional authorities and private technology enterprises contributed different kinds of knowledge. The Czech Geological Survey produced and maintained foundational geological information; the Czech Hydrometeorological Institute operated essential networks for meteorology, climatology, hydrology and air quality; the national surveying and cadastral administration supplied authoritative spatial reference information. Universities developed interpretative theory, specialist analytical methods and generations of researchers, while the Academy of Sciences sustained long-term investigations not always compatible with short project cycles. Environmental information agencies and statistical offices linked scientific evidence with the requirements of public administration. The achievements of the period depended less on the supremacy of one organisational model than on the possibility of transferring questions, observations and skills among these institutions.

The coexistence of these organisations also reveals a structural difficulty. Public-service observation, doctoral scholarship, competitive research and operational forecasting are governed by different standards of success. A continuously functioning hydrometric station is invaluable even when it does not immediately produce a journal article. A theoretical study of spatial inequality may change scholarly understanding without offering a direct administrative prescription. A geological database can serve several decades of later research while appearing less innovative than a short-lived application. The Czech experience suggests that assessment systems become misleading when they treat every scientific activity as though it should yield the same output at the same pace. Sustained scientific performance required both the maintenance of national evidence and the freedom to investigate questions whose significance was not fully apparent at the point of funding.

Prague remained a central location for geographical and geoscientific research, but centrality did not imply national uniformity. Charles University retained a strong combination of physical geography, social geography, demography, regional development, cartography and geoinformatics. The Czech Geological Survey, numerous Academy institutes and important professional organisations reinforced the capital's scientific density. Yet Masaryk University in Brno developed distinctive expertise in geographical analysis, environmental research and interdisciplinary applications, while Palacký University Olomouc became particularly prominent in cartography and geoinformatics. Ostrava combined research related to geoinformatics, environmental change, industrial landscapes and geotechnical conditions. Other universities and regional workplaces contributed specialised investigation of landscapes, water resources and local development. This geographical distribution matters:

problems rooted in the Moravian lowlands, the industrial north-east, the Bohemian borderlands or mountain headwaters demanded regional knowledge that could not be generated entirely from a national centre.

Regional research schools were not sealed intellectual territories. A doctoral graduate trained in one city might undertake observation through a state institute, process data provided by another university and publish in an international collaboration. The growing sophistication of instruments and methods often increased interdependence rather than competition between specialisations. Expertise in remote sensing could support forestry, geomorphology and urban studies; hydrological modelling depended on atmospheric inputs, terrain representations and land-cover descriptions; demographic work drew upon statistics and geographical classification. As scientific careers became more international, a school could no longer be defined only by a particular building or professor. Its continuity resided in shared research problems, transmitted methodological standards and the ability to renew these through students and collaborators. This flexible understanding of scientific tradition helps explain why institutional change did not necessarily interrupt Czech disciplinary development.

Physical geography and geoecology offer one of the clearest examples of continuity through methodological transformation. The Czech lands provided a well-documented landscape of uplands, sedimentary basins, river valleys, agricultural lowlands and heavily modified industrial areas. Long traditions in landscape science, biogeography and geomorphological interpretation enabled researchers to examine this diversity as an interconnected set of processes rather than a catalogue of regional peculiarities. Between 1993 and 2025, the balance shifted increasingly towards process explanation, measurable environmental interactions and the comparison of contemporary change with historical trajectories. Questions of erosion, floodplain transformation, habitat fragmentation, soil degradation and water retention could be investigated through field measurements, historical documents, spatial statistics and numerical models. The consequence was a strengthening of geography's capacity to explain why apparently similar physical settings responded differently to human pressure.

Landscape research also demonstrated the insufficiency of a strict separation between nature and society. Czech environments carried the legacies of historical settlement, collectivised agriculture, industrial extraction, forest management and infrastructure development. Land use was an ecological variable, a political outcome and an expression of economic opportunity at the same time. The long-term land-use research associated with Ivan Bičík, Leoš Jeleček and their collaborators connected historical statistical evidence with the geographical interpretation of modern change. The reconstruction of land use from the nineteenth century to the post-socialist decades was particularly significant because it exposed the limits of explanations based solely on recent observation. Contemporary habitat conditions and water responses frequently reflected decisions made generations earlier. The resulting research became a bridge between historical geography, physical geography, regional development and environmental assessment.

This historical perspective helped correct a common misunderstanding of the post-1993 landscape: the disappearance of one economic system did not produce an immediate

ecological reset. Agricultural restructuring could bring reductions in cultivation pressure to some marginal areas while commercial investment intensified construction around cities. Former industrial districts could experience declining emissions alongside enduring soil contamination and subsurface hazards. Mountain ecosystems could be affected simultaneously by past atmospheric pollution, contemporary forest management and changing climatic conditions. It followed that apparently favourable national indicators could conceal regionally concentrated degradation, just as a local improvement might be obscured by aggregate trends. Czech physical geographers increasingly recognised that scientific evaluation required comparisons across temporal scales and the integration of physical indicators with land ownership, planning institutions and economic incentives.

Mountain and protected landscapes became important settings for testing these approaches. The Krkonoše, Šumava, the Jeseníky and other upland regions offered contrasts in altitude, snow conditions, forest structure, tourism intensity and the persistence of historical disturbance. Research on high-elevation soils, periglacial forms, slope processes and hydrological headwaters connected regional field observation with wider discussions of climatic sensitivity. Protected status did not remove these territories from human influence; rather, it created a particularly visible arena in which conservation objectives, visitor pressure, timber management and regional livelihoods had to be negotiated. As detailed terrain models and satellite observations became available, researchers could document spatial patterns with new precision. Yet measurement could not by itself determine which ecological condition should be prioritised, reminding scientists and planners that landscape management includes normative choices beyond the reach of physical models.

The Czech experience of geoecological research further emphasised the value of comparison across contrasting land-use histories. Abandoned industrial sites, intensively farmed lowlands, regenerating forests and peri-urban landscapes could be analysed as different outcomes of human intervention within broadly comparable climatic settings. Work in environmental geography at the Institute of Geonics was especially relevant to questions crossing the conventional physical–human divide. Such research challenged the idea that environmental damage is solely an issue of pollutants or biological change. The location of deprived communities, local perceptions of risk, patterns of economic restructuring and the capacities of municipal institutions influence whether environmental recovery is politically and socially possible. By the end of the study period, the most persuasive landscape scholarship was often interdisciplinary not because its authors abandoned geography, but because geographical explanation required several forms of evidence to be considered together.

Geology followed a partly different trajectory because its most important achievements rested upon exceptionally long observational and documentary accumulation. The Czech Geological Survey inherited geological maps, borehole records, mineral-resource evaluations, field descriptions and archives covering far more than the independent republic's lifetime. The post-1993 challenge was to preserve these holdings while making them useful to a society in which property relations, construction activity, environmental standards and resource priorities were changing. Geological investigation increasingly had to inform the remediation of contaminated locations, assessments of engineering conditions, groundwater protection and land-use

planning, as well as the reconstruction of the Earth's past. These applications did not displace fundamental science. On the contrary, they exposed the practical relevance of precise stratigraphy, structural geology, petrology and geochemistry, whose conclusions depend on detailed knowledge of geological history.

The Survey's development illustrates the interaction between institutional change and scientific infrastructure. Its assumption of the name Czech Geological Survey in 2002, the integration of the Geofond component in 2011 and the progressive digitisation of cartographic holdings made geological information more coherent and accessible. National geological mapping at 1:50,000 scale provided an authoritative reference, while more detailed mapping at 1:25,000 concentrated on selected territories and newly emerging priorities. These products were not static illustrations: they were repeatedly reinterpreted as understanding of rock units, structural relationships and environmental hazards improved. Their significance extended to groundwater studies, radon assessment, resource planning, engineering geology and landscape research. The ability to connect a specific field observation with a national geological framework illustrates the infrastructural achievement behind many less visible advances in Czech Earth science.

Fundamental geological research retained an international dimension independent of immediate domestic applications. The Bohemian Massif, the Western Carpathians and their associated sedimentary successions continued to provide important evidence of tectonic evolution, metamorphism, magmatism and the assembly of European crustal structures. Palaeontological and stratigraphic research linked Czech localities with international chronostratigraphic debates; the historical significance of the Silurian–Devonian boundary at Klonk exemplifies the enduring global value of a well-studied site. Laboratory developments improved the measurement of geochemical signatures and geological ages, while field surveys supplied the contextual control needed to interpret them. Czech geological scholarship therefore participated in a dialogue between intensely local evidence and models of continental-scale Earth history. The scientific standing of a national community did not depend on the size of its territory, but on the interpretative significance and reliability of observations made within and beyond it.

Post-mining and industrial landscapes brought an especially strong applied dimension to geological research. Regions affected by coal extraction, spoil heaps, subsidence, abandoned underground workings and contaminated deposits demanded combinations of geological mapping, engineering assessment, geophysics and environmental monitoring. The Ostrava region and the northern Bohemian mining districts presented different histories of extraction and different possibilities for ecological and economic transformation. Research could describe the physical stability of a site or identify contaminant pathways, but successful restoration also depended on finance, planning, public consultation and alternative employment. Geoscience thus became an essential contributor to regional transition rather than an autonomous technical service. The wider lesson was that geological knowledge could reduce uncertainty about the ground, while decisions about its future use remained embedded in social and political processes.

The increasing relevance of subsurface questions extended into energy, waste management and water security. Investigations of mineral deposits, geothermal possibilities, groundwater systems and potential deep geological repository sites placed sophisticated geological expertise within long-term public choices. These fields required caution about uncertainty: a numerical model of fractured rock is useful precisely when its assumptions, boundary conditions and limitations are recognised. National research institutions had to communicate that uncertainty to policymakers and citizens without confusing scientific qualification with indecision. The period demonstrated how Earth science could contribute to decisions extending far beyond a normal research project. It also exposed the need for stable archives and traceable datasets, since future generations must be able to examine the evidence underlying decisions about subsurface facilities and environmental liabilities.

Geomorphology retained its identity through the close reading of landforms, sediments and processes, yet it too moved towards a more explicitly quantitative and interdisciplinary practice. Czech researchers addressed the evolution of river terraces, hillslopes, mountain relief, karst systems and Quaternary deposits by combining field geomorphology with sediment analysis, geochronology and detailed topographic information. Earlier descriptive traditions supplied an indispensable vocabulary of forms and regions. Newer analytical techniques made it possible to test competing explanations of timing, rates and causal mechanisms. The resulting progress was not simply the replacement of field notebooks by digital elevation models. It was the recognition that topographic pattern can be measured rapidly but its history must be reconstructed from independent geological, sedimentary and ecological evidence. Methodological pluralism became an important safeguard against interpreting visually convincing patterns too confidently.

Research on fluvial landscapes revealed how modern geomorphology could link fundamental and applied questions. River channels respond to floods, sediment supply, engineering structures, land use and changes in catchment connectivity. An embanked reach may appear stable while incurring a deficit of sediment, loss of floodplain functions or increased exposure downstream. Geomorphological studies helped explain why flood protection cannot be evaluated solely through the dimensions of a single channel. They also highlighted the importance of river restoration, riparian processes and the historical transformation of wetlands. In this work, geomorphology was not a subsidiary of hydrological forecasting; it supplied the longer temporal perspective needed to understand why runoff and sediment responses differed among neighbouring catchments. Czech contributions were particularly relevant in a country where intensive historical land use has profoundly altered the relationship between rivers and their floodplains.

The development of high-resolution terrain mapping was decisive for this field but did not eliminate uncertainty. Airborne laser scanning, terrestrial surveys and later unmanned aerial observations allowed scientists to detect small relief forms, trace abandoned channels, map slope failures and investigate erosion features obscured in conventional maps. Repeated observations opened the possibility of measuring short-term landscape change rather than merely inferring it from geomorphic form. These advantages also introduced scale-related difficulties. A feature identifiable in a detailed local model may disappear at regional

resolution, while an algorithm may classify roughness as a process indicator when vegetation, survey geometry or historical land disturbance is responsible. Czech geomorphological research consequently illustrates a broader epistemological point: improved spatial resolution increases the number of hypotheses that can be tested, but does not automatically resolve which hypothesis is correct.

The boundaries of Czech geomorphology also became wider than the national territory. Research carried out in high mountain and polar environments permitted comparison between Czech upland processes and settings where glaciers, permafrost or extreme relief were more pronounced. International fieldwork strengthened methodological training and introduced new questions concerning deglaciation, sediment dynamics and rapid environmental change. Such work did not constitute a departure from national geography. Instead, it increased the explanatory power of comparisons applied to the Bohemian Massif and its surroundings. The strongest scientific traditions were those capable of treating the Czech Republic as a carefully observed reference case within a larger geography of Earth-system processes, rather than as the absolute boundary of legitimate research.

Climatology and meteorology were transformed through the encounter between persistent observational obligations and the emergence of climate change as a defining public concern. The Czech Hydrometeorological Institute continued to maintain essential station networks, forecasting services and climatic archives, preserving continuity with earlier national and international measurement systems. Automatic observations, radar, satellite information, numerical weather prediction and improved data processing gradually altered the scale and speed of meteorological analysis. Yet the scientific value of these technologies depended on calibration, historical comparability and skilled interpretation. A long series affected by a station relocation or a change in observing practice cannot be treated uncritically as a homogeneous record. The achievements of Czech climatology lay partly in the ability to exploit new data while protecting the integrity of older evidence. This combination enabled researchers to distinguish fluctuations of weather from longer-term changes in climatic distributions and extremes.

The evolution of climatic research can also be traced through a change in the central questions asked. During the early post-socialist years, air pollution, regional climatic characterisation and the modernisation of observational services remained prominent. Subsequently, investigations increasingly addressed heatwaves, changing snow conditions, precipitation extremes, drought, urban heat and the consequences of a warming climate for ecological and economic systems. These research themes did not replace classical synoptic meteorology or atmospheric physics; they made their integration with climatology more necessary. A heatwave requires investigation of atmospheric circulation and surface energy exchange, but its societal consequences depend upon urban morphology, housing, vegetation and health vulnerability. Czech climate research thus became part of a larger interdisciplinary enterprise in which physical mechanisms had to be related to spatially differentiated human exposure.

The Climate Atlas of Czechia, published in 2007, provides a telling example of the enduring role of national synthesis. Its combination of thematic maps, climatic indicators and explanatory material transformed a dispersed body of observations into a geographical representation

suitable for scientific investigation, education and public consultation. An atlas is sometimes mistaken for the conclusion of research rather than its infrastructure. In practice, a coherent representation of climatic variation creates questions about regional gradients, exceptional locations, environmental sensitivity and possible changes in the spatial distribution of conditions. It permits users from outside climatology to approach technical information with a consistent frame of reference. The atlas therefore embodies a central achievement of the period: the translation of specialist observation into an accessible, spatially organised account without depriving the underlying measurements of their scientific complexity.

An equally important development was the rise of interdisciplinary research into global change. CzechGlobe, with its roots in earlier research groups and its consolidation through a European centre of excellence around 2010, came to represent a mode of investigation in which atmospheric conditions, ecosystem processes and socioeconomic consequences were studied in relation to each other. Measurements of exchanges of energy, water and greenhouse gases, remote observation of vegetation and modelling of environmental change helped connect local field sites with global scientific debates. This did not remove the need for conventional meteorological services. Rather, it created opportunities for exchange between long-term monitoring, experimental ecosystem science and scenario-based assessment. The scientific strength of such cooperation depended on distinguishing measured trends, model projections and policy scenarios instead of presenting them as interchangeable kinds of knowledge.

Drought research illustrates this transformation especially clearly. Drought is not a single phenomenon that can be determined by one weather indicator. Meteorological deficits, depleted soil moisture, reduced river flow, declining groundwater levels and agricultural impacts may begin at different times and persist for different durations. The dry episodes experienced during the 2010s, including the pronounced multi-year pressures of the second half of that decade, made these distinctions important beyond academic debate. Czech research and monitoring increasingly integrated meteorological records, agricultural information, soil and catchment models and remote-sensing observations. Such integration improved the capacity to describe the geographical extent and intensity of emerging stress. It also made visible the limits of purely technical responses: reservoir capacity, soil management, land-use planning and household demand determine whether an atmospheric deficit becomes a socially damaging shortage.

Research on urban climates similarly revealed the social relevance of spatially detailed physical analysis. Temperature conditions within Prague, Brno or other settlements cannot be characterised adequately by one regional weather station. Building density, impervious surfaces, street orientation, vegetation, ventilation and the distribution of vulnerable residents influence how heat is experienced. The growing availability of remote sensing and urban spatial datasets supported more differentiated assessment, yet the translation of such findings into cooling strategies remained politically contingent. A tree canopy may provide measurable thermal benefits, but its distribution depends on land ownership, street design, maintenance budgets and competing infrastructure needs. In this respect climatology converged with social geography and urban planning: the mapping of a hazard became scientifically complete only

when exposure, adaptive capacity and unequal access to protective environments were examined.

Aerology and atmospheric physics contributed a further level of explanation by extending investigation beyond near-surface weather. Upper-air soundings, atmospheric remote sensing, radar observations and modelling made possible more detailed analysis of circulation, stability, transport and atmospheric interactions. Research undertaken in specialised Academy institutes and university departments placed Czech observations within global networks concerned with the dynamics of the atmosphere and near-Earth environment. Such work could appear distant from territorial planning, yet it supported forecast development and the interpretation of phenomena that influence conditions at the surface. The historical lesson is that applied benefits frequently depend on intellectual and observational capabilities whose initial rationale is fundamental rather than immediately practical. Scientific systems oriented exclusively towards short-term utility risk weakening the knowledge on which later improvements depend.

Climatic observation also became inseparable from the communication of uncertainty. A probabilistic forecast is not a categorical promise; a climate projection is conditional upon assumptions about emissions and the climate system; and a reconstructed long-term trend remains sensitive to record quality and the definition of the variable. Public demand for clear guidance can encourage excessive simplification, particularly during extreme events. Czech meteorological and climate institutions consequently faced a task wider than producing measurements or models. They had to make uncertainty intelligible without undermining trust in well-supported findings. That challenge became characteristic of geographical and Earth sciences as a whole, especially as their evidence entered decisions about public safety, infrastructure investment and adaptation to environmental risk.

Hydrology and hydrogeology developed within a landscape where major floods and increasingly persistent dry conditions exposed different aspects of water vulnerability. The floods of 1997 and 2002 were decisive public events, prompting renewed attention to catchment response, forecasting arrangements, warning systems and the consequences of building in flood-prone areas. Subsequent floods, including those of 2013 and 2024, reinforced the need to examine extremes as processes involving atmospheric circulation, precipitation, antecedent moisture, river networks and exposure. Research on flooding became more differentiated as hydrometric networks, hydrological models, topographic information and real-time communication improved. Importantly, an extreme event did not constitute a controlled experiment. Its interpretation required comparison with earlier records, evaluation of the reliability of measurements and recognition that protective infrastructure can change both hydraulic behaviour and patterns of vulnerability.

Flood science offered a compelling demonstration of the limits of administrative boundaries. Precipitation and runoff do not respect municipal or national borders, while the impacts of channel modification or reservoir operation can extend far downstream. The Czech Republic occupies important portions of the Elbe, Oder and Danube drainage systems, providing a geographical setting in which river-basin cooperation is indispensable. European water policy and the Floods Directive reinforced this catchment-based perspective by requiring the

assessment of risks beyond isolated localities. Yet the utility of such frameworks depended on detailed Czech knowledge of headwaters, land cover, reservoirs, river morphology and settlement. International standards helped organise comparison; they could not replace the empirical specificity of national observation. The resulting research culture combined basin-wide modelling with the investigation of local processes and institutional responsibilities.

Catchment hydrology became increasingly sensitive to the effects of land-cover change and forest disturbance. A flood hydrograph reflects not only rainfall intensity but also soil properties, storage conditions, drainage systems, slopes, snow processes and the continuity of flow pathways. Czech researchers used experimental catchments and hydrological modelling to investigate such interactions, particularly in upland headwaters and areas affected by forest management or environmental disturbance. These studies resisted simplified claims that a single intervention could prevent every type of flood. Woodland, wetlands and soil conservation can provide important hydrological functions, but their effectiveness varies with storm magnitude, antecedent saturation and catchment geometry. A scientifically credible policy therefore requires scale-specific assessment rather than the unqualified transfer of results from one location to another.

Snow hydrology added another dimension because Czech headwaters depend on seasonal accumulation and melt despite the country's lack of very high alpine terrain. In mountain regions, changes in winter temperature can alter the proportion of precipitation falling as snow, the timing of meltwater delivery and the duration of soil moisture recharge. These changes affect river-flow seasonality, ecosystem conditions, winter tourism and water management. The interaction between climate variability and catchment storage makes it difficult to infer future discharge from temperature trends alone. Investigations of snowpack, precipitation phase and runoff formation thus demonstrate why climate and hydrology must be interpreted together. By the later decades of the period, the scientific issue was not merely whether snow conditions had changed, but how altered winter processes would interact with summer demand and the geographical distribution of water resources.

Groundwater research followed slower temporal rhythms that made it particularly important during episodes of prolonged drought. Aquifers store water within geological settings whose capacity, recharge pathways and vulnerability differ substantially. Observed fluctuations in groundwater levels cannot be understood adequately without considering geological structure, precipitation history, land use and abstraction. The Czech Geological Survey's synthesis of national groundwater knowledge, alongside hydrogeological monitoring and university investigations, supported a more integrated understanding of subsurface water systems. Groundwater also posed difficult governance questions: contamination may persist after an industrial activity has ceased, and unsustainable abstraction can remain politically attractive before its full consequences become evident. The field therefore required both sophisticated geoscientific interpretation and an unusually long planning horizon.

Water-quality research provided evidence of environmental change that could not be captured by the measurement of discharge alone. Post-socialist industrial restructuring, improved wastewater treatment, changing agricultural practices and evolving environmental regulation influenced the transport of nutrients and contaminants through rivers and groundwater.

Positive changes in some pollution indicators did not eliminate diffuse agricultural pressures, legacy contamination or newly recognised substances of concern. Hydrochemistry, ecological indicators and catchment analysis became mutually reinforcing, especially within the European Water Framework Directive's emphasis on water-body condition. In practical terms, the requirement to understand chemical concentrations also demanded knowledge of hydrological timing, dilution, sediment transport and biogeochemical transformation. Hydrology's development towards an integrated science of water was consequently not optional; it followed from the nature of the environmental problems facing Czech territory.

The juxtaposition of flood and drought research exposes a deeper conceptual lesson. Both hazards involve the temporary distribution of water across a landscape, yet the institutions, public perceptions and investments associated with them can be strikingly different. Floods attract immediate attention because damages are visible, whereas depletion of groundwater or soil moisture may accumulate silently. A dam, drainage scheme or land-cover intervention may influence these hazards in different, sometimes conflicting, ways. Czech research increasingly provided the analytical means to compare such trade-offs across time and space. The challenge for science was to identify physically credible options; the challenge for policy was to decide how benefits, risks and costs should be distributed. These are related questions but should not be confused. Their distinction became a recurrent feature of mature applied geography.

Economic geography underwent a change of explanatory framework more directly associated with the transformation of society after 1989 and the establishment of the republic. Privatisation, enterprise restructuring, foreign investment, altered trade relations and the expansion of services reshaped the national economy's spatial organisation. Established industrial regions faced contraction and diversification, while Prague and other metropolitan areas gained new roles in finance, specialised services and international business networks. Peripheral territories experienced divergent outcomes depending on their accessibility, labour markets, institutional capacities and inherited economic structures. The crucial achievement of Czech economic geography was not to produce a single map of prosperity and decline, but to demonstrate why territorial inequality persisted even while national economic indicators improved. Regional differentiation was recognised as an enduring structural property rather than an incidental failure of adjustment.

The scholarship associated with Martin Hampl was influential in interpreting geographical hierarchies, uneven development and the selective character of societal transformation. His work linked theoretical questions concerning geographical organisation with empirical investigation of post-socialist change. This was significant because the move towards a market economy could not be understood by simply applying economic growth figures uniformly across space. Institutions, settlement hierarchies and historically formed concentrations of activity affected where opportunities emerged. Subsequent research on regional development, labour mobility and industrial restructuring expanded these insights through more varied analytical methods. The enduring contribution was a geographical argument: economic transformation produces differentiated territorial consequences, and explanations must account for the spatial organisation through which social processes operate.

European integration sharpened both the opportunities and contradictions addressed by regional research. Cross-border cooperation, structural funds and increasing economic connectivity altered the development context of districts formerly shaped by protected or relatively impermeable borders. Participation in European production networks strengthened certain metropolitan and industrial locations, but it did not automatically remove disparities between centres and peripheries. Accessibility to transport corridors, educational institutions and administrative capacity influenced the effective use of new opportunities. Regions could therefore benefit from international investment while remaining vulnerable to decisions made outside their territory. Czech economic geography supplied tools for interpreting this dependence and for evaluating development policies more critically than would be possible through expenditure totals or aggregate employment growth alone.

The geography of industrial transition was especially revealing because economic and environmental processes occurred in the same locations. Former mining territories and manufacturing districts carried costly material legacies even as their labour markets and identities changed. Brownfield redevelopment might represent a new investment opportunity, a response to land scarcity or an attempt to repair environmental damage. Whether such a project improved territorial development depended on its relation to surrounding communities, transport, housing and public services. Research into regional restructuring consequently converged with studies of land contamination, urban planning and social vulnerability. The Czech case illustrates that the economic re-use of a site and its ecological recovery are not synonymous, although they can reinforce each other when planning objectives and scientific evidence are appropriately aligned.

The transition to a knowledge-intensive economy also transformed the map of scientific and technological activity itself. Universities, research centres, technology enterprises and specialised labour markets became elements of regional development rather than external observers of it. The concentration of advanced research infrastructure in major centres could produce valuable clusters of expertise, while raising questions about unequal access to education and professional careers. Geographical research contributed to the assessment of innovation networks, institutional proximity and the uneven regional effects of public investment. Such analysis offered a corrective to the assumption that more scientific funding must generate identical benefits everywhere. It suggested instead that successful knowledge-based development depended upon relationships among skills, firms, public organisations and local conditions, and upon a willingness to examine who could participate in these relationships.

Social geography and demography revealed transformation at the scale of everyday life. Population change, household formation, commuting, migration, education and unequal health outcomes took place within settlements whose physical forms and institutional boundaries had been shaped over generations. Czech research moved beyond simple descriptions of population distribution towards the analysis of residential mobility, segregation, suburbanisation and the geography of social opportunity. The demographic censuses of 2001, 2011 and 2021 offered successive reference points, but their use required attention to changing definitions, collection methods and territorial units. The increased

availability of statistical information did not remove the need for interpretation. A municipal growth rate might reflect metropolitan displacement, international migration, a change in housing supply or changes in registration practice. The essential contribution of geographical analysis was to investigate these mechanisms rather than treat a demographic indicator as its own explanation.

Prague's metropolitan development became a particularly important research setting. The expansion of suburban housing, changing commuting patterns and the differentiation of neighbourhoods made visible the interaction of property markets, municipal planning and transport infrastructure. Research associated with Martin Ouředníček and other urban geographers illuminated the spatial consequences of suburbanisation and the social complexity hidden by broad metropolitan averages. Comparable processes, although differing in scale and history, were investigated around Brno and other regional centres. These studies showed that a suburban municipality could experience rapid residential growth without an equivalent increase in local employment or public facilities. At the same time, some inner-city districts underwent redevelopment and social change. The geographical question was therefore not simply whether cities expanded, but how metropolitan restructuring redistributed time, opportunity, environmental burdens and the capacity of local governments to respond.

Migration research placed Czech territorial change within a wider European and global context. The country was no longer adequately understood only through the departure and return of its own citizens; immigration, labour mobility, international education and transnational households became consequential for population geography and public policy. The scholarly work associated with Dušan Drbohlav helped establish migration as a central concern of Czech social geography, linking empirical investigation with debates about integration and mobility. Yet aggregate migration balances conceal substantial differences between regions, occupations, generations and legal statuses. A research system capable of evaluating these differences could challenge both simplistic narratives of demographic crisis and assumptions that labour mobility is an exclusively economic process. Geography's contribution was to show how migrants navigate particular housing markets, workplaces, institutions and social environments, rather than an abstract national space.

Political geography examined the changing meanings of territory during the same period. The independent republic's borders were simultaneously historical inheritances, administrative jurisdictions and sites of new cooperation. Czech accession to the European Union in 2004 and participation in the Schengen area from 2007 altered the practical experience of many internal European borders, although border functions did not disappear. Research on borderlands explored accessibility, identity, cross-border labour markets, local governance and the legacies of earlier geopolitical division. The Czech–Slovak relationship offered a distinctive example of scientific and social continuity after state separation, while connections with Germany, Austria and Poland developed in different economic and cultural circumstances. Political geography thereby moved beyond the depiction of boundaries as lines to the analysis of institutions, flows and historically conditioned perceptions of neighbouring territories.

Questions of territorial governance also linked political geography with regional and environmental science. Changes in administrative organisation, the establishment of self-governing regions and the interaction between municipal, national and European responsibilities affected how spatial problems were defined. A watershed, metropolitan labour market or protected ecosystem seldom coincided neatly with one administrative jurisdiction. Researchers could identify a functional region, but public authorities still had to coordinate action across their formal competences. This mismatch was particularly evident in transport planning, flood protection, landscape conservation and the management of metropolitan growth. The scientific importance of political geography lay in making such differences explicit, showing why otherwise persuasive territorial strategies might fail when authority, finance and accountability were fragmented among institutions.

Geodesy provided a less publicly visible but equally fundamental foundation for this expanding spatial science. Satellite positioning, permanent observation networks, high-precision levelling, gravimetry and geodynamic investigations improved knowledge of the Earth's geometry and of deformation affecting reference coordinates. The Czech research community participated in European and global observing systems while maintaining national requirements for cadastral accuracy, surveying and infrastructure development. The scientific issue was not simply the achievement of smaller measurement errors. Coordinates have meaning only within defined reference systems, and repeated observations must account for stability, transformations and the distinction between physical movement and measurement artefact. Developments in precise geodesy therefore supported every discipline needing to combine observations made by different instruments, institutions or generations of researchers.

The connection between geodesy and atmospheric science became particularly instructive. Satellite navigation signals pass through the atmosphere, so precise positioning requires modelling of propagation effects, while the same measurements can yield information relevant to atmospheric water vapour. Techniques developed for one purpose can thus become sources of evidence for another. Permanent Czech geophysical and GNSS networks, including those coordinated through CzechGeo and connected with European research infrastructures, illustrated the benefits of such reciprocal use. Seismological, gravimetric and geodynamic observations also linked domestic monitoring with international analysis of crustal processes. The broader achievement was the emergence of research infrastructure in which reliable measurement could outlive the needs of an individual project and acquire unforeseen scientific value through subsequent interpretation.

Cartography and geoinformatics transformed the representation and analysis of territory without rendering earlier cartographic scholarship irrelevant. Digital maps widened access, permitted interactive exploration and facilitated the combination of data that had formerly been distributed across printed sheets or institutional archives. However, every map remained a selection and interpretation of reality. Research schools associated with Milan Konečný, Vít Voženílek and colleagues developed approaches concerned with geographical information systems, cartographic communication, visual cognition, thematic representation and the evaluation of mapping interfaces. Such contributions were important because the usefulness

of a spatial dataset depends partly on how it is conceptualised and communicated. More detailed cartography can improve public understanding, but poorly chosen classifications, colours or scales can also intensify misunderstanding. The development of digital technology consequently increased rather than diminished the need for rigorous cartographic theory.

The national tradition of thematic atlases makes this continuity tangible. The Climate Atlas of Czechia, the Landscape Atlas of the Czech Republic and the Academic Atlas of Czech History assembled different bodies of evidence, yet all demonstrated the scientific value of coherent spatial synthesis. They revealed relationships that might remain obscure in isolated tables, case studies or written descriptions. At the same time, their production required decisions about scale, classification, temporal comparison and uncertainty. Digital dissemination later broadened the possibilities for revision and interaction, while preserving the underlying intellectual challenge of creating a meaningful geographical account. A landmark atlas was thus more than a collection of attractive maps. It was an argument concerning what belonged together in the spatial interpretation of a country and what differences merited attention.

The establishment of interoperable geospatial services gradually changed the status of scientific and administrative data. Databases maintained by the Czech Geological Survey, the land-surveying administration, the Czech Statistical Office and environmental authorities became increasingly available through searchable catalogues, standardised services and public portals. European INSPIRE requirements supported the development of common descriptions and exchange mechanisms, while improvements in open-data policy encouraged reuse beyond the original custodians. The central achievement was not that every dataset became unrestricted or perfectly compatible; such a claim would ignore differences of scale, licensing, confidentiality and quality. Rather, an infrastructure emerged in which data could be discovered, evaluated and recombined more systematically. This altered what individual researchers could investigate without building an entire observation network of their own.

International cooperation shaped these developments but should not be represented as one-way transmission from larger scientific centres to a smaller national system. Czech researchers contributed long observation series, expertise in the Bohemian Massif, sophisticated knowledge of Central European settlement and land-use histories, and specialised methods of environmental and spatial analysis. International programmes supplied opportunities for comparison, technical development and shared training, while foreign field sites offered tests of hypotheses generated from domestic experience. Cooperation through European research frameworks, geological networks, meteorological organisations and transboundary river institutions demonstrated different models of scientific integration. Some prioritised common instruments; others focused on methodological standards, data exchange or joint interpretation. Their shared lesson was that international standing is sustained through reciprocal scientific contribution rather than formal membership alone.

The widening openness of Czech geography also created new expectations concerning scientific responsibility. Accessible data and visually convincing analytical outputs can be reused by audiences who have not encountered the qualifications attached to their production. Researchers must therefore explain uncertainty, protect sensitive information and

distinguish observed relationships from causal inference. Demographic mapping can expose small communities to stigmatisation; precise locations of vulnerable ecological features may require care; environmental models can create misleading confidence when assumptions are hidden. These concerns do not justify retreat from public science. They suggest instead that responsible openness requires documentation, reproducible methods, proportional restrictions and sustained dialogue with users. The public value of geography rests on making evidence usable without creating the illusion that every territorial question has a purely technical solution.

Important limitations remained visible by 2025. Research infrastructure was unevenly distributed; funding arrangements did not always favour long observational commitments; and competition for international publication could undervalue Czech-language synthesis and highly specialised public services. Data interoperability progressed faster in some fields than others. Complex models could be difficult to audit, and results generated at different scales were sometimes compared as though their assumptions were identical. Interdisciplinary projects faced the additional challenge of reconciling evidence that followed different temporal rhythms, from atmospheric measurements recorded minute by minute to geological processes reconstructed over millions of years. Recognising these limits is essential to a balanced historical evaluation. A successful scientific system is not one without weaknesses, but one able to identify them, preserve critical capacity and make informed adjustments.

The principal opportunities beyond the end of the period follow from the same historical experience. Climate adaptation requires the integration of atmospheric forecasts, groundwater knowledge, land management and socially differentiated vulnerability. Sustainable regional development demands understanding of industrial transformation, demographic ageing, mobility and ecological limits. Disaster-risk reduction depends on observation networks, reliable maps, clear communication and institutions capable of acting across administrative boundaries. The continuing expansion of satellite measurements, automated monitoring and analytical computation may improve these efforts, provided that it is accompanied by transparent validation and stable support for fundamental research. Neither artificial intelligence nor larger databases can replace the scientific judgement required to select meaningful indicators, challenge assumptions and interpret place-specific histories. Czech geography’s future strength will depend on its ability to use emerging techniques without surrendering its critical understanding of scale, territory and long-term change.

Seen across the entire period, the trajectories of the twelve fields considered in this book converge upon a common conclusion. Geology and geodesy supplied enduring material and spatial reference systems; climatology, meteorology and hydrology observed the dynamics of atmosphere and water; geomorphology and geoecology explained the transformation of landscapes; economic, social and political geography investigated the organisation of human activity; and cartography and geoinformatics connected diverse forms of evidence through spatial representation and analysis. Their methods and institutional histories were not identical, nor should they have become so. Their cumulative achievement was the emergence of a research culture increasingly able to recognise that environmental and societal questions

cross disciplinary boundaries while still requiring specialist expertise. Between 1993 and 2025 the Czech Republic demonstrated how a relatively compact scientific community could combine inherited records, rigorous field investigation, theoretical renewal and international collaboration. The lasting significance of this experience lies in the conviction that knowledge of territory is most valuable when it explains change without neglecting history, supports action without concealing uncertainty and remains open to questions that the present has not yet learned to ask.

Chronological Timeline

Geography and Earth Sciences in the Czech Republic, 1993–2025

This chronology records selected, verifiable milestones in the development of Czech geography and Earth sciences between the establishment of the independent Czech Republic in 1993 and the end of 2025. The sequence encompasses institutional change; the development of observing systems, research facilities and spatial-data infrastructures; landmark publications; scientific programmes; and major environmental events that redirected research priorities. It is intentionally selective rather than a catalogue of every project or publication. Events are assigned to the year of their documented occurrence, while multi-year programmes are identified through their launch, substantial completion or another verifiable milestone.

The category labels distinguish institutions, research schools, infrastructure, publications, policy frameworks, international cooperation and hazards, but the boundaries between these fields are necessarily porous. European directives and national policy decisions are included when they materially changed the scientific and administrative setting for Czech research. The interpretive comments explain why a dated event matters; they should not be mistaken for claims that an entire field changed within a single calendar year.

Year	Field / category	Milestone and historical significance
1993	Institutions	On 1 January, the independent Czech Republic and the Academy of Sciences of the Czech Republic began operating within the new state framework. The inherited observational, mapping and university traditions were reorganised rather than replaced wholesale.
	Research schools	The transformation of the former academic geography institute resulted in the Brno Centre for Environmental Geography within the Institute of Geonics. This ensured continuity of interdisciplinary regional and environmental research despite institutional discontinuity.
	Scientific communication	Moravian Geographical Reports published its first volume. The English-language journal became a durable forum linking geographical research in Moravia with wider international debates.
	Institutions	On 1 April, the former Ostrava Mining Institute was renamed the Institute of Geonics of the Academy of Sciences, bringing mining-oriented geoscience and a Brno-based geographical research group into a new institutional setting.

1994	Scientific community	The Czech Geographical Society held its eighteenth congress in Prague during its centenary celebrations. The meeting marked the adaptation of a long-established scholarly society to the independent Czech Republic.
	Digital methods	Geographical and environmental researchers in Olomouc established a joint EKO-GIS workplace. Early investment in digital spatial-data processing provided a foundation for later geoinformatics teaching and research.
1995	Geospatial infrastructure	Production of the Fundamental Base of Geographic Data of the Czech Republic (ZABAGED) began through the digitisation of large-scale national topographic map sources. This initiated the transition from separately printed maps towards a continuously maintained national spatial database.
	Institutions	Changes in state nature conservation produced the Administration of Protected Landscape Areas and a distinct professional nature-conservation agency. The institutional separation influenced landscape inventory, monitoring and the practical use of ecological geography.
	Land-use research	Leoš Jeleček published a historical analysis of land-use changes in the Czech Republic, 1845–1995, placing contemporary transformations within a long record of agricultural and environmental change.
1996	Observational infrastructure	The Czech Hydrometeorological Institute (ČHMÚ) commissioned a meteorological radar at Skalky in Moravia. Improved radar observation increased the capability to monitor precipitation and developing hazardous weather.
	Geographical scholarship	From volume 101, the Czech Geographical Society's journal adopted the title Geografie – Sborník České geografické společnosti. Its 1996 issues included major contributions on the geography of societal transformation and long-term land-cover change.
	International cooperation	The Czech Republic concluded a framework cooperation agreement with the European Space Agency (ESA), initiating a relationship that would later support national involvement in Earth observation and satellite-related research.
1997	Hydrological hazards	The exceptional July floods in the Morava and Odra catchments stimulated a sustained re-examination of rainfall–runoff processes, flood forecasting, floodplain exposure and inter-agency risk communication.

	Academic training	Palacký University Olomouc introduced geography–geoinformatics studies. This was an important step towards educating a distinct generation of specialists in GIS, remote sensing and thematic cartography.
1998	Environmental information	Act No. 123/1998 Coll. established a framework for access to environmental information. The legal context supported wider public use of monitoring results and environment-related geographic information.
	Scientific community	The Czech Geographical Society convened its nineteenth congress in Prague, maintaining national exchange among physical, social and regional geographers during the post-socialist transformation.
1999	Forecasting services	ČHMÚ established its Central Forecasting Office. The concentration of operational forecasting functions helped connect instrumental observations, numerical modelling and warning services.
	Geoinformatics training	Additional specialised GIS facilities were created in Olomouc, strengthening the technical and teaching base from which the separate Department of Geoinformatics subsequently emerged.
2000	Observational infrastructure	ČHMÚ commissioned a new meteorological radar on the summit named Praha in the Brdy Mountains. Together with the Moravian radar, it strengthened national precipitation surveillance and severe-weather diagnostics.
	Geospatial information	The Czech Geological Survey began its 2000–2004 programme of digitising the geological map archive. The programme made historical cartographic evidence increasingly accessible for comparison and reuse.
	European framework	The EU Water Framework Directive was adopted. Although Czech implementation followed through national and European processes, its river-basin orientation became influential for hydrology, water-quality research and environmental planning.
	Geographical scholarship	Ivan Bičík and Martin Hampl published a review of Czech human geography, its research priorities and unresolved problems, helping articulate the discipline's post-socialist agenda.
2001	Geoinformatics institutions	On 1 September, the Department of Geoinformatics was separated from the Department of Geography at Palacký University Olomouc, under the leadership of Vít Voženílek. The new department consolidated GIS and cartographic methods as an independent academic specialism.

	Spatial statistics	The population and housing census supplied a major independent-state reference dataset for migration, settlement, labour-market and regional inequality analysis.
	Geospatial infrastructure	The initial vectorisation phase of ZABAGED was largely completed, apart from the built-up-area detail. Work continued towards a seamless, attributed national geodatabase.
2002	Hydrological hazards	The destructive August floods, especially in Bohemia, renewed investigation of the Vltava and Elbe catchments, hydrometeorological extremes, hydraulic modelling and the relationship between spatial development and flood losses.
	Institutions	The Czech Geological Institute adopted the name Czech Geological Survey; the parallel geological-information organisation also used the Czech Geological Survey–Geofond name. The changes anticipated later consolidation of national geological information services.
	Polar research	Czech geologists undertook research activities in Antarctica, strengthening the country's contribution to international polar geoscience before the construction of a permanent Czech station.
2003	Geoscientific communication	Bulletin of Geosciences was developed as a prominent outlet for Czech and international geological research. Its growing international profile supported the visibility of stratigraphic, palaeontological and other Earth-science work.
	Academic training	Palacký University's Department of Geography opened an International Development Studies programme, widening the connection between Czech geographical education, development processes and global regional questions.
	Space cooperation	An agreement concerning the Czech Republic's participation in the ESA Plan for European Cooperating States was concluded, preparing closer engagement with space-science and Earth-observation programmes.
2004	European integration	On 1 May, Czech EU accession established a new institutional framework for regional development, environmental reporting, cross-border research and harmonisation of geospatial information.
	National mapping	ZABAGED reached coverage of the Czech Republic with its defined objects and attributes assembled into a seamless digital geographical database. Continuous updating became the next central challenge.

	Geodesy	Construction of CZEPOS, the Czech network of permanent GNSS stations for positioning, began. It created the basis for real-time precise positioning and broader geodetic interoperability.
	Remote sensing	The airborne remote-sensing group later incorporated into CzechGlobe acquired an AISA Eagle hyperspectral scanner, opening new possibilities for field-calibrated vegetation and environmental observation.
	Space cooperation	The ESA Plan for European Cooperating States charter was signed in Prague, providing a formal route for Czech participation in ground-segment, space-science and Earth-observation activities.
2005	Environmental information	On 1 April, CENIA, the Czech Environmental Information Agency, was established as a successor to the Czech Ecological Institute. It became an important provider of validated environmental information, map services and national reporting.
	Geodesy	CZEPOS began providing post-processing data in March and real-time services in June. Its station network transformed the practical availability of precise GNSS positioning across Czech territory.
	National mapping	The first comprehensive update of ZABAGED was completed, combining remote sensing, field revision and improved attribute information with digital topographic maintenance.
	Polar infrastructure	Construction began on the Czech research station on James Ross Island, Antarctica, led by Masaryk University. The facility was intended to support interdisciplinary polar field research.
2006	Polar infrastructure	Construction of the Czech Antarctic station on James Ross Island was completed in February. From this point the station provided a logistical base for Czech and international seasonal expeditions.
	Academic training	Palacký University's Department of Geography established a specialist programme in regional geography, reflecting renewed demand for systematic analysis of territorial differentiation.
	Nature-conservation institutions	The national nature-conservation agency was reorganised through the integration of professional conservation and protected-area administrative functions. This strengthened the operational links between monitoring, field documentation and landscape management.

	Geodetic infrastructure	CZEPOS implemented network positioning solutions during the year, improving services designed for centimetre-scale GNSS applications and surveying practice.
2007	Scientific publication	The bilingual Atlas podnebí Česka (Climate Atlas of Czechia), coordinated by Radim Tolasz and produced by ČHMÚ and Palacký University, presented a comprehensive new cartographic synthesis of the national climate.
	Geological publication	The Czech Geological Survey published the Geological Map of the Czech Republic at 1:500,000 scale, offering a national-scale synthesis useful for research, education and territorial assessment.
	European spatial policy	The INSPIRE Directive established a European framework for interoperable environmental spatial information. Its requirements shaped the later construction of Czech metadata, viewing and download services.
	Hydrological policy	The EU Floods Directive established a common basis for evaluating and managing flood risks, encouraging the use of mapped exposure, hazard scenarios and periodically updated assessments.
	Polar infrastructure	The Czech Mendel Antarctic station was officially opened on 22 February. It enabled regular multidisciplinary expeditions and long-term observations in the Antarctic Peninsula region.
	Research governance	A change in Czech legislation converted many institutes of the Academy of Sciences, including the Institute of Geonics, into public research institutions, altering their governance and operating framework.
2008	International cooperation	On 12 November, the Czech Republic became a full member of ESA. This opened wider participation in European space missions, Earth observation, satellite instrumentation and data-processing collaborations.
	Geological data integration	The Czech Geological Survey participated in the launch of OneGeology-Europe, which sought interoperable geological mapping at European scale and included Czech work on a multilingual metadata catalogue.
	Airborne science	Czech airborne environmental researchers participated in the EUFAR European airborne research collaboration, strengthening international expertise in imaging spectroscopy and multi-scale observation.

2009	Landmark atlas	The Atlas krajiny České republiky (Landscape Atlas of the Czech Republic) was published, integrating natural, cultural and socio-economic information in a major interdisciplinary cartographic synthesis.
	Land-use scholarship	Ivan Bičík and Leoš Jeleček published an analysis of Czech land-use and landscape change during the transition of 1990–2007, relating cadastral-scale evidence to restructuring after socialism.
	Geospatial services	The second comprehensive update cycle of ZABAGED reached completion. Repeated revision demonstrated that a national geographical database required ongoing observation rather than one-time digitisation.
2010	Global-change research	The CzechGlobe centre-of-excellence initiative began to take shape, integrating atmospheric, ecosystem and socio-economic research under a common global-change agenda.
	University infrastructure	Palacký University's Department of Geography moved into the new Faculty of Science building in Olomouc, improving its facilities for academic teaching and interdisciplinary research.
	Scientific communication	From volume 115, the long-established journal of the Czech Geographical Society used the shorter title Geografie. The change reflected its mature identity as an international academic journal.
	Research infrastructure	The CzechGlobe investment programme for 2010–2015 began to expand laboratory, field and airborne capacities for global-change studies.
2011	Spatial statistics	The population and housing census of March 2011 introduced an online response option alongside conventional collection, supporting a new generation of geographical analyses of settlement and society.
	Geological services	The administrative consolidation of the Czech Geological Survey and its Geofond branch entered its final stage; their integrated organisational arrangement became effective at the beginning of 2012.
	Polar geoscience	Czech Geological Survey research reported distinctive Antarctic fossil discoveries, illustrating the scientific possibilities of sustained field campaigns in polar environments.
2012	Reference geodata	RÚIAN, the Register of Territorial Identification, Addresses and Real Estate, entered production on 1 July. Standardised reference

		identifiers greatly strengthened the capacity to join spatial and administrative datasets.
	Hydrogeological synthesis	The Czech Geological Survey issued Podzemní vody České republiky (Groundwater of the Czech Republic), a major reference synthesis of national hydrogeological knowledge.
	Drought monitoring	Experimental operation of the Intersucho drought-monitoring system began at 500 m spatial resolution, marking a shift towards spatially explicit and regularly updated agricultural-drought assessment.
	Data interoperability	ČÚZK introduced harmonised INSPIRE download services for cadastral parcels, connecting the national cadastral infrastructure with European spatial-data standards.
	Scientific communication	Moravian Geographical Reports was selected for coverage in Web of Science products, indicating the growing international visibility of an established Czech regional and environmental geography journal.
2013	Hydrological hazards	Widespread flooding in June, particularly within the Elbe and Vltava basins, generated new comparative material for hydrological extremes, forecast performance and risk governance after the floods of 1997 and 2002.
	Spatial-data interoperability	ČÚZK completed INSPIRE harmonisation and launched viewing and download services for address and administrative-unit themes.
	Geographical publishing	The online distribution of Moravian Geographical Reports expanded through an international scholarly publishing platform, supporting accessibility beyond its original institutional audience.
2014	Landmark atlas	Akademický atlas českých dějin (Academic Atlas of Czech History), edited by Eva Semotanová and Jiří Cajthaml, appeared as a major historical cartographic synthesis combining archival interpretation with geographical representation.
	Geospatial policy	Government Resolution No. 815 of 8 October approved the national Strategy for the Development of Spatial Information Infrastructure to 2020 (GeoInfoStrategie). It formalised priorities for public-sector geodata coordination and interoperability.
	Drought infrastructure	The Intersucho web portal began publicly presenting drought conditions and a network of field reporters. Its integration of modelling and observations increased the visibility of soil-moisture research.

	Remote sensing	Czech airborne researchers entered the EUFAR-2 cooperation phase, expanding their participation in European airborne imaging and environmental investigations.
2015	Landmark publication	Ivan Bičík and colleagues published Land Use Changes in the Czech Republic 1845–2010: Socio-Economic Driving Forces (Springer), consolidating long-term cadastral evidence and explanations of Czech landscape transformation.
	Airborne infrastructure	CzechGlobe's Flying Laboratory of Imaging Systems (FLIS) began operating, giving Czech environmental research a specialised platform for high-resolution imaging spectroscopy and other airborne observations.
	Climate policy	The Czech Republic adopted its first national Strategy on Adaptation to Climate Change, creating a stronger policy context for climate-impact modelling, vulnerability mapping and the assessment of adaptation options.
	Spatial-data interoperability	ČÚZK completed harmonisation and launched INSPIRE viewing and download services for the Buildings theme.
2016	Institutions	The Global Change Research Institute of the Czech Academy of Sciences, known as CzechGlobe, acquired its formal institutional status, building on the earlier centre-of-excellence project and established global-change research groups.
	European geological infrastructure	The Czech Geological Survey became a founding participant in the European Geological Data Infrastructure (EGDI), strengthening access to harmonised geological knowledge across national borders.
	Earth-observation cooperation	Prague hosted ESA's Living Planet Symposium, bringing a major international Earth-observation research meeting to the Czech Republic.
	Ecosystem infrastructure	The CzeCOS infrastructure-upgrading project started in July, expanding research equipment for experimental and observational investigation of ecosystem processes.
2017	Adaptation policy	A national Action Plan on Adaptation to Climate Change was adopted, translating national adaptation strategy into more concrete programmes and giving geographical risk analysis a stronger implementation context.

	Polar research	Regular expeditions continued at the Czech Mendel Antarctic station, strengthening the cumulative observation record in glaciology, climatology, ecology and geological field science.
2018	Geological information	The Czech Geological Survey introduced web-map applications adapted for mobile phones and tablets, broadening practical access to national geological data and thematic layers.
	International airborne research	CzechGlobe's airborne team participated in the FlexSense project under ESA auspices, extending expertise in hyperspectral calibration, environmental remote sensing and sensor evaluation.
	European geophysical infrastructure	EPOS ERIC was established at European level, consolidating a long-running framework for interoperable solid-Earth research services to which Czech geophysical infrastructures could contribute.
2019	Climatological publication	Martin Hynčica and Radan Huth published Long-term changes in precipitation phase in Czechia in Geografie, documenting the importance of changes in winter precipitation type for interpreting regional climate trends.
	Ecosystem infrastructure	The 2016–2019 expansion of CzeCOS was completed, strengthening CzechGlobe's distributed instrumental base for ecosystem observation and global-change research.
	Digital scholarship	By the end of the decade, Czech geographical journals, agencies and universities increasingly relied on online dissemination and searchable geospatial outputs, a cumulative transition rather than a single institutional launch.
2020	Open geodata	From 1 January, ČÚZK made qualifying spatial datasets available as open data under a CC BY 4.0 framework. This preceded the wider liberalisation of topographic and orthophoto data in 2023.
	Uncrewed observation	CzechGlobe's airborne activities expanded to include an unmanned aircraft system equipped with hyperspectral and thermal sensors, adding a flexible platform for detailed ecosystem monitoring.
	Scientific communication	Moravian Geographical Reports became electronic-only with volume 28, reflecting the migration of Czech scientific communication towards digital publication.
	Research programmes	CzechGlobe entered the European eLTER preparatory-phase project, designed to strengthen the foundations of coordinated long-term ecosystem and socio-ecological research.

2021	Spatial statistics	The 2021 population and housing census was organised predominantly online and drew extensively on administrative registers, opening new possibilities for harmonised territorial statistics.
	Climate adaptation	The national Adaptation Strategy and its Action Plan were updated, reflecting increasingly urgent demands for climate-risk assessment and evidence-based territorial policy.
	Drought science	Intersucho introduced the SoilClim2 model and expanded its monitoring and forecasting activities to a global scale.
	Extreme weather	The destructive June tornado in South Moravia gave renewed urgency to research on convective extremes, warning dissemination, exposure and territorial resilience.
2022	Spatial statistics	Major thematic and territorial outputs from the 2021 census were published, supplying updated baselines for research into urbanisation, demographic structures and regional change.
	Geoscience infrastructure	Czech geoscientific organisations continued integrating long-term measurement series and digital map services with European information environments, including EPOS-related solid-Earth data provision.
	International cooperation	During the Czech presidency of the Council of the European Union in the second half of the year, European environmental and research-policy coordination provided a broader setting for the country's scientific networks.
2023	Open geodata	On 1 July, ZABAGED, national orthophotography, digital state map products, geographical names and geodetic control data became freely available as open data. This was a decisive change in public access to core geographical information.
	National cartography	New Basic Topographic Maps of the Czech Republic were first released on 1 July, replacing older map series with standardised products derived from contemporary digital topographic data.
	Infrastructure integration	The information system supporting regional Digital Technical Maps (IS DMVS) went into production, preparing the exchange of infrastructure and spatial-reference data among authorities and network operators.
	Scientific communication	Palacký University's Department of Geography joined the Institute of Geonics as a co-publisher of Moravian Geographical Reports,

		formalising cooperation between an academic journal and a university centre.
	Remote-sensing cooperation	CzechGlobe's airborne research unit joined PRISCAV cooperation with Italy's CNR concerning calibration and validation activities connected to the PRISMA imaging-spectroscopy mission.
2024	Digital technical maps	On 1 July, the national Digital Technical Maps framework entered full operational production, connecting regional systems and providing more structured spatial information on physical and technical infrastructure.
	Hydrological hazards	Exceptional September flooding in Moravia and Silesia supplied a major test of contemporary precipitation observation, hydrological forecasting, risk communication and the analysis of compound environmental extremes.
	Geological research	The Czech Geological Survey reported research connected with a potential deep geological repository for radioactive waste, illustrating the role of Earth sciences in technically demanding, long-term environmental decisions.
	European cooperation	The EPOS science programme for 2024–2028 set priorities for the development of federated European solid-Earth services, within which Czech monitoring and research infrastructures operated.
2025	Environmental information	CENIA marked twenty years since its establishment, demonstrating the consolidation of a national system for integrating environmental evidence, digital information services and public reporting.
	Drought services	The Intersucho portal continued its development, including a revised web interface, more than a decade after the initial operational monitoring and the first public portal launch.
	Geographical scholarship	Volume 33 of Moravian Geographical Reports included work on geodiversity and geoheritage, illustrating the continued international publication of research on conservation, landscape change and geographical methods.
	Long-term observation	The European eLTER preparatory-phase project, in which CzechGlobe participated, reached the scheduled end of its 2020–2025 phase, illustrating how Czech ecosystem research was embedded in shared European infrastructures.

Interpretive overview

The first decade was dominated by the reorganisation of scientific institutions, the preservation of specialist research communities and the initial shift from analogue production to digital observation. The launch of ZABAGED and the early adoption of GIS were especially important because they changed the form in which spatial evidence could be maintained and reanalysed. The floods of 1997 and 2002 established a parallel imperative: geographical and Earth-science knowledge had to be usable in risk assessment and public warning, not merely in descriptive accounts of the environment.

Between EU accession in 2004 and the mid-2010s, Czech research became more closely embedded in European policy and infrastructure frameworks. ESA membership, INSPIRE, national GNSS services, harmonised cadastral identifiers and major thematic atlases illustrate different aspects of the same transition. Scientific disciplines gained new opportunities for cross-border comparison while becoming more dependent on shared standards, databases and long-term institutional funding. The development of CzechGlobe and dedicated airborne facilities connected this integration to global-change research.

The final decade combined open-data reform, stronger climate-adaptation requirements and research responses to recurring drought and extreme rainfall. The 2023 expansion of open national topographic data and the 2024 deployment of digital technical maps improved the infrastructure through which spatial evidence circulates. At the same time, the September 2024 floods showed that improved observations do not eliminate hazard exposure. By 2025 the Czech research system had become substantially more digital and international, although the task of translating knowledge into equitable and effective territorial decisions remained unfinished.

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SCIENTIFIC EDITIONS

Alexander Buychik

IMPLEMENTATION OF INNOVATIONS IN BIOLOGY: EXPERIENCE OF THE CZECH REPUBLIC

Computer typesetting — Tuculart Studio

Signed for editing on October 30, 2026.

Format: ISO 216, 8.27*11.69 in. (21.0*29.7 cm)

Tuculart Edition European Institute for Innovation Development
Czechia, 71000, Ostrava, Slezská Ostrava, Zámostní, 1155/27
Czechia, 74752, okr. Opava, Hlavnice, 163
Websites: https://tuculart.eu, https://eiid.eu
Emails: pub@tuculart.eu, pub@eiid.eu, eiid.ostrava@gmail.com

Right to conduct publication activities



ISBN 978-80-88474-59-3
DOI 10.47451/book-2026-23