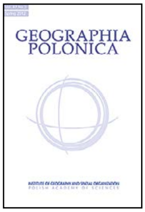

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CHALLENGES IN GEOENVIRONMENTAL RESEARCH – NATURAL AND ANTHROPOGENIC INTERACTIONS

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Abstract

The geoenvironment – characterised by dynamic interactions among its various components – is continually evolving under the impact of climate change and human activities across diverse temporal and spatial scales. This special issue brings together six studies that aim to address existing knowledge gaps concerning the interplay between natural processes and human activities within different morphoclimatic zones. The contributions are organized into three overarching thematic categories: (1) transformations of the natural environment in the context of climate change, (2) assessments of anthropogenic pollution in soils and water bodies, and (3) geodynamic processes in river valleys, including aspects of water management and environmental protection. This introductory paper synthesizes the findings presented in the special issue and outlines potential directions for future research in geoenvironmental studies. Emphasis is placed on the effects of climate change and anthropogenic impacts, approached through interdisciplinary perspectives and supported by advanced research methodologies. Such an approach will open new opportunities for global-scale analysis of geoenvironmental transformations and is vital for informing sustainable development strategies.

Keywords

geoenvironment • natural processes • human impact • climate change • environmental complexity and interactions

Introduction

The geoenvironment is a complex system characterized by dynamic interactions among its components, including geological structure, relief, climate, surface and underground water, soils, flora, fauna, and also anthropogenic activities (Aswathanarayna, 2018; Goudie, 2018; Cendrero et al., 2022; Chenchouni et al., 2023; Dai et al., 2025). Its current state and future changes are determined by both long-term natural processes (Henry et al., 2007) and increasing human impacts (Raju, 2022; Bucała-Hrabia, 2023). Climate variability, hydrologic alterations, and human-induced land degradation are driving significant transformations within the geoenvironment – often with outcomes that are uncertain and difficult to forecast. Contemporary research on environmental change underscores the importance of incorporating historical context to better understand present dynamics and anticipate future developments in the geoenvironment (Hannaford, 2024; Kanyiginya et al., 2025). A holistic, interdisciplinary approach that considers human-environmental relations is essential for understanding the complex mechanisms that govern the geoenvironment, and for improving the accuracy of predictive models. Furthermore, the application of modern research tools – such as modeling, remote sensing, and geostatistical analysis – is crucial for assessing and monitoring environmental changes. These advanced technologies enable more precise tracking of geoenvironmental transformations and offer improved insights into their long-term implications.

In this context, the scientific conference 'Geoenvironment – Climate, Nature, Man', organised by the Department of Geoenvironmental Research at the Stanisław Leszczycki Institute of Geography and Spatial Organization of the Polish Academy of Sciences in Krakow (Poland), held on 5 April 2024, provided a valuable platform for presenting cutting-edge research and facilitating the exchange of ideas among scientists, practitioners, and environmental experts. The event explored both theoretical and applied aspects of the geoenvironment functioning, with particular emphasis on the roles of climate, environmental change, and human activity. Key discussions addressed the challenges of adapting to evolving climatic conditions and underscored the necessity of integrating actions at local, regional, and global scales to support sustainable development. By fostering interdisciplinary dialog and knowledge sharing, the conference contributed to a more nuanced understanding of the geoenvironment's complexity. It also highlighted the critical need for continued research and systematic monitoring to inform effective environmental protection strategies and climate change mitigation efforts.

Special issue content

The articles featured in this issue examine the geoenvironment as a complex system wherein natural and anthropogenic elements coexist and interact within distinct geographical contexts. Contemporary geoenvironmental research increasingly focuses on evaluating the impacts of human activities on the natural environment, alongside deepening our understanding of the Earth processes that shape these interactions. This issue presents six original research studies that offer valuable perspectives on the pressing challenges currently affecting the geoenvironment across various regions and ecosystems. The contributions are organized into three thematic sections covering (i) transformations of the natural environment in the context of climate change, (ii) assessments of anthropogenic pollution in soils and water bodies, and (iii) geodynamic processes in river valleys, including aspects of water management and environmental protection.

Climate change stands as one of the most significant challenges of our time, with its global effects manifesting through altered weather patterns, an increased risk of extreme flooding and drought, rapid loss of sea ice, and rising sea levels. Trenberth

(2011) notes that the intensification of rainfall is unevenly distributed across the globe – while some regions face prolonged droughts, others are experiencing heavier precipitation events. Furthermore, the frequency of floods has increased in certain areas (Rhoads, 2020). A recent study, included in this issue, conducted by Rituparna et al. (2025) focusing on the Patharpratima region of India (1990-2020) analyzed the impacts of sea level rise, increasing sea surface temperatures, and cyclone intensity on coastal erosion and mangrove degradation. Employing advanced statistical models, the researchers project that by 2030, the coastline will retreat further inland, posing heightened risks to both human populations and natural ecosystems. In addition to climatic factors, anthropogenic land clearing for agriculture has emerged as a significant driver of mangrove loss in the Indian coastal zone, thereby exacerbating vulnerability to erosion and flooding. The study underscores the urgent need for integrated environmental management strategies to preserve regional biodiversity and enhance climate resilience. The use of advanced shoreline assessment models – specifically Endpoint Rate and Shoreline Change Envelope – addresses a critical research gap by providing robust methods for evaluating mangrove dynamics under climate change pressures (Gilman et al., 2008).

The global temperature increase – 1.1°C higher during the period 2011-2020 compared to the pre-industrial baseline (1850-1900) (IPCC, 2021) – has significant implications for urban climates as well (Smid et al., 2019; Kuchcik et al., 2024). Climate change, compounded by rapid urban expansion, necessitates a deeper understanding of urban thermal patterns. A recent study by Czarnecka (2025), employing a multidimentional approach at the urban scale, investigates the spatial thermal structure of Warsaw (Poland) between 2002 and 2018. The research identifies thermal hot and cold spots using integrated survey methodologies, reveailing a complex urban thermal mosaic. The findings underscore the intricate relationships between thermal hot and cold spots, land cover, urban morphology, and local air temperature regimes. Such studies are essential for enhancing urban planning practices and developing more precise strategies for climate change mitigation and adaptation in metropolitan environments.

The impacts of climate change are often difficult to isolate due to the effects of other driving forces, particularly human activities, which can either mitigate or intensify environmental changes (Goudie, 2018; Cendrero et al., 2022). All components of the environment are undergoing significant transformations largely driven by anthroponenic interventions (Kabir et al., 2023). In this special issue, Jelonek et al. (2025) highlight the important role of recreational areas as sources of persistent solid waste, including microplastics, glass, and metals, which are slow to degrade. Their study, conducted around the Sosina Reservoir in the Upper Silesian Industrial District (Jaworzno, Poland), reveals that intensified human activity has led to elevated concentrations of certain elements, such as mercury and molybdenum, exceeding reference thresholds and posing potential ecological and public health risks. The highest pollutant levels were detected in areas near the beach, where human presence is most concentrated. The application of optical microscopy in the study provided critical insights into the physical composition of soils, complementing traditional physical and chemical analyses to better understand the migration pathways of solid contaminants. Soil monitoring of this kind is essential for implementing appropriate protective, ensuring user safety, and safeguarding environmental quality.

Soil contamination in the vicinity of water bodies can significantly impair water quality through infiltration and leaching of pollutants. Human activities such as the disposal of post-mining waste further exacerbate these impacts, as demonstrated by a study of 16 water bodies in the Upper Silesian Coal Basin (Sołtysiak et al., 2025). The research revealed elevated levels of electrical conductivity and high concentrations of sulfate, chloride, and sodium – key indicators of chemical pollution. These effects are largely attributed to the prolonged oxidation of pyrite within post-mining waste, which facilitates the leaching of contaminants and leads to moderately or high levels of water pollution in the reservoirs. The degree of contamination is influenced by multiple factors, including the function and size of the reservoir, the mineralogical and chemical composition of the surrounding waste, and the proximity to waste dumps (Jiao et al, 2023). The most severe contamination occurs in stagnant water bodies in direct contact with large volumes of waste rock. Additionally, even reclaimed mine waste dumps remain a latent source of groundwater contamination, particularly affecting the shallowest aquifer. This poses a potential risk if such aquifers are used as drinking water sources.

In reservoir systems, water quality degradation is frequently linked to the accumulation of nutrients and organic matter, which promotes eutrophication – characterized by rapid growth of production surges and phytoplankton blooms (Istvánovics, 2010; González, Roldán, 2020). A recent study of the Sulejowski Reservoir in central Poland by Karim et al. (2025) showed that the reservoir primarily acts as a nutrient sink. However, during periods of low water discharge combined with intense phytoplankton blooms, it may also act as a secondary source of nutrients. The study further revealed that the formation and structure of eddies within the lake zone of the reservoir significantly influence phytoplankton distribution. While such hydrodynamic features have been widely examined in oceanographic context (Mohn, White, 2007), they have rarely been documented in detail in small inland reservoirs in Poland. Notably, the application of remote sensing with multispectral satellite imagery in this research has demonstrated strong potential for advancing reservoir ecology by providing continuous spatial monitoring of phytoplankton distribution.

River flows, both contemporary and historical, have played a crucial role in shaping river valleys, with transported sediments serving as vectors for substances that affect the surrounding environment. The infrastructure within river valleys (modern and historical) is strongly linked to these environmental processes. Geoarchaeological research conducted by Szmańda et al. (2025) at Bulwar Filadelfijski in Toruń revealed that landslide and fluvial sediments – both channel and off-channel deposits from the Vistula River – surrounding the uncovered foundations of a medieval Benedictine monastery and the Church of the Holy Spirit, provide clear evidence of intense denudation and fluvial activity. This is further evidenced by the presence of redeposited Bronze Age and Roman pottery fragments, likely displaced during medieval flood events. The study notes that from the late Middle Ages onward, following the construction of defensive wall and the monastery buildings, the area became primarily covered with embankment deposits. Subsequently, after the mid-17th-century destruction of the complex, overbank alluvium, especially from ice-jam winter floods typical of the Toruń region, was deposited in the area. This research exemplifies how the integration of geomorphological, sedimentological, archaeological, and historical data enables a comprehensive reconstruction of past human-environment interactions.

The topics explored in this volume are essential for advancing the understanding of environmental processes across a range of disciplines, including natural and anthropogenic hazard assessment and mitigation, engineering, land conservation and restoration, landscape and urban planning, ecosystem evaluation, and the assessment of natural heritage.

Future research directions

Despite substantial advancements in geoenvironmental research, significant knowledge gaps remain, particularly in our limited ability to accurately predict long-term changes in the geoenvironment resulting from the complex, synergistic interactions between natural processes and anthropogenic impacts. Future research should prioritize the incorporation of uncertainty into climate change models, especially with regard to its impacts on geomorphological, hydrological, and soil-forming processes. Addressing the integration of diverse spatial and temporal scales in geoenvironmental studies also remains a critical challenge, one that is essential for developing effective adaptation and management strategies.

The findings presented by the authors in this special issue further underscore the need for continued investigation. This includes research into thermally heterogeneous climatic structures that persist year-round in urban areas, as well as comprehensive assessment of microclimatic features, including bioclimatic conditions. There is also a pressing need to expand research on reservoirs, which can function both as sinks and sources of pollutants. In particular, detailed analysis of eddy dipole structures in the reservoir are needed, as they can extend water residence times and induce vertical fluxes of nutrients from deeper reservoir leyers.

Looking ahead, geoenvironmental research – particularly on the effects of climate change and human activity across diverse morphoclimatic zones – will require an interdisciplinary approach that leverages advanced measurement techniques, modern research tools, and spatial modeling. Such an approach will open new opportunities for global-scale analysis of geoenvironmental transformations and is vital for informing sustainable development strategies.

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