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Progress and Outlook of Environmental Geology Research Techniques in China

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ABSTRACT: Environmental geological research, centered on the interaction between humans and the geological environment, is a critical field aimed at promoting harmony between human activities and the Earth system. It has garnered widespread attention in both domestic and international geological communities. This paper briefly reviews the historical development of environmental geology as a discipline and systematically summarizes the major advances and existing challenges in environmental geological research worldwide. In light of China's ongoing ecological civilization initiatives and future development needs, the study emphasizes that environmental geology represents a vital mission for geological work in the new era. Future research should focus on key areas such as urban geology, sustainable utilization and management of water resources, monitoring and integrated prevention of geological hazards, protection of ecological and environmental systems, and studies related to the Earth's critical zone. The paper highlights the importance of interdisciplinary approaches and the systematic application of new technologies and methods, aiming to support the rational development of natural resources while safeguarding the geological environment.

KEYWORDS: Environmental geology; Resources; Environment; Progress; Prospect

1. INTRODUCTION

The geological environment serves as a fundamental basis for human survival and development. With the rapid growth of the global population and accelerated economic development, human activities have exerted profound impacts on the geological environment, leading to increasingly frequent global environmental geological issues with significant social consequences. Over the past three decades, China has experienced rapid industrialization and urbanization, resulting in drastic changes in land use, intensified exploitation of land, groundwater, and mineral resources, and prominent problems such as groundwater depletion, geological hazards, mining-related environmental geological issues, and environmental pollution[1].As of the end of 2016, 24 provinces (autonomous regions and municipalities) across China had reported varying degrees of groundwater overexploitation, with 191 groundwater depression cones covering approximately 84,000 km². Ground subsidence was recorded in nearly 102 prefecture-level cities in 21 provinces (autonomous regions and municipalities)[2 3]. Since 2011, sudden geological disasters in China have caused direct economic losses exceeding 31 billion yuan, remaining a major constraint on socioeconomic development. Groundwater and soil quality conditions are generally concerning, with severe soil contamination issues in certain farmlands and abandoned industrial and mining sites[4].These challenges have intensified the contradictions among resources, the environment, and population, posing serious threats to human survival and sustainable development[5]. Under new circumstances, there is an increasingly urgent need for environmental geological work to support China's socioeconomic development and environmental protection goals. In accordance with China's "Five-sphere Integrated Plan" and the ecological civilization development strategy, it is of critical importance to correctly understand the impacts of human activities on the geological environment, and to grasp the characteristics and patterns of regional environmental geological problems[6]. This constitutes a major mission for geological work in the new era and holds significant practical implications for rational resource utilization, geological environment protection, and the promotion of harmony between humans and nature.

Based on a brief review of the development of environmental geology, this paper summarizes the major advances in environmental geological research both domestically and internationally, and explores future trends and directions. This work aims to help define key areas of focus for China's environmental geology in the new era, and better serve the needs of socioeconomic development, environmental protection, and the advancement of the discipline[7].

2. HISTORICAL REVIEW OF ENVIRONMENTAL GEOLOGICAL RESEARCH

As a product of the evolving relationship between humans and the Earth, environmental geology centers on the study of human–environment interactions, aiming to promote sustainable development between humanity and nature. It has become a focal point of interest in both domestic and international geological communities. In terms of disciplinary scope, environmental geology can be interpreted in both broad and narrow senses. In its broad sense, it encompasses subfields such as environmental hydrogeology, environmental engineering geology, environmental geochemistry, and ecological geological studies, positioning it within the broader domain of environmental science. In the narrower sense, environmental geology mainly focuses on issues related to human activities, including groundwater, geological hazards, mining-related geological environments, and soil–water environmental systems. This paper adopts the narrow definition, emphasizing the primary areas of environmental geological work in China. It reviews the evolution and development of the discipline both domestically and internationally, analyzes current progress, and discusses future directions for environmental geology, with the aim of promoting the advancement and practical implementation of related work in this field[8-10].

2.1 Initial stage of environmental geological research

Environmental geology originated in the 1960s and 1970s as a response to the increasing need to mitigate the adverse impacts of human activities on nature and to support the demands of societal development. During this period, industrialized countries such as the United States, the United Kingdom, and West Germany began to recognize the urgency of environmental geological problems. Issues such as geological hazards and the exploitation of natural resources were incorporated into the scope of environmental geological research. Flawn (1970) was among the earliest to discuss the concept and research scope of environmental geology. Later, Burton (1978) and Alexander (1983) emphasized that the core objective of environmental geology is to understand the interactions between the geological environment and human activities, to identify the characteristics and patterns of geological hazards, and to predict their future trends. This period marked the initial stage of environmental geological research. In China, awareness and attention to environmental geological issues remained relatively limited at that time. Research efforts were primarily driven by the needs of urban development and economic growth. A small number of specialized surveys were carried out in hydrogeology, engineering geology, and geochemistry. Relevant studies were conducted on groundwater exploitation, land subsidence, and endemic geological diseases, laying the groundwork for future development of the discipline.

2.2 Development stage of environmental geological research

In the 1980s and 1990s, the concept of sustainable development gained widespread global consensus. The release of key international documents such as the Declaration on Environment and Development and Agenda 21 marked a turning point, prompting the international scientific community to launch major initiatives including the International Geosphere-Biosphere Programme (IGBP) and the International Decade for Natural Disaster Reduction (IDNDR). Against this backdrop, environmental geology—focusing on environmental and disaster-related issues—garnered extensive attention from the global geoscience community. It gradually evolved into a recognized sub-discipline of geology and catalyzed rapid development in environmental geological research. During this period, Keller (1982) defined environmental geology as an applied branch of geology that employs geological theories and methods to study the interactions between human activities and the environment. The goal is to reduce the negative environmental impacts of human activities and to propose practical solutions. Subsequently, many Western countries launched environmental geological mapping programs, groundwater resource and quality assessment projects, and other initiatives aimed at supporting geological hazard risk assessment and mitigation, land-use evaluation and environmental planning, groundwater protection and water quality improvement, hazardous waste site selection, key engineering site assessment, and environmental impact assessments related to mineral resource exploitation. Research in this stage primarily focused on topics such as geological hazards (including earthquakes, volcanic eruptions, landslides, ground subsidence, and threats from radioactive and toxic wastes), coastal environmental issues (such as shoreline changes, wetland degradation, bay and estuary pollution, and flood disasters), groundwater resource protection and management, the environmental impacts of energy development, ecosystem conservation and agricultural development, as well as urban environmental geological problems.

Environmental geological research in China began in the 1980s, driven by the needs of major infrastructure projects and rapid urban development during the period of national reform and opening-up[11-13]. A number of domestic scholars introduced the concept of environmental geology and engaged in in-depth discussions and research, eventually reaching several key points of consensus:

Environmental geology is an emerging applied discipline within the geological sciences and constitutes an important component of environmental science.

Environmental geology integrates theories and methods from geological science, environmental science, and other related disciplines to study the fundamental characteristics, functions, and evolutionary patterns of the geological environment, as well as its interactions and mutual influences with human activities.

In a broad sense, the subject of environmental geology is the complex system formed by human society and the geological environment, involving interactions among the lithosphere, atmosphere, hydrosphere, and biosphere.

Environmental geology is committed to serving the goals of sustainable development.

During this period, reforms within China's geological departments and the implementation of a series of strategic programs significantly advanced the development of environmental geology as a discipline. Notably, in 1988, the former Ministry of Geology and Mineral Resources (renamed the Ministry of Land and Resources in 1998) was assigned the responsibility for geological environment protection, which extended the scope of environmental geology to include areas such as geological hazard prevention and control. Environmental geological research in China during this stage primarily focused on regional environmental geological surveys and mapping, studies on water resource development and associated ecological issues, as well as the prevention and mitigation of geological hazards. A number of major projects were undertaken, including specialized investigations of geological hazards along major rivers and key transportation corridors, evaluations of water resources and geological environments in critical regions across the country, and environmental geological surveys in major cities centered on water supply, engineering construction, and hazard mitigation. Comprehensive environmental geological map series were compiled for the Yangtze and Yellow River basins, along with thematic maps focusing on groundwater and geological hazards. These efforts laid the foundation for the initial establishment of a nationwide geological environment monitoring network, making important contributions to national economic development and social progress. In addition, research on mining-related environmental geology also received increasing attention and underwent substantial development[14-17].

2.3 Rapid development and refinement stage of environmental geological research

Since the beginning of the 21st century, global and regional collaboration has become a key organizational model for environmental geological research. Core research themes have expanded to include global climate change, sea level rise, and large-scale material and energy cycles. Environmental geology has entered a stage of rapid development and refinement. Countries such as the United States and those in Europe have progressively adopted a problem-oriented and demand-driven approach to environmental geological research. Efforts have deepened and broadened across various domains, including climate and land-use change, water resource utilization and protection, early warning and forecasting of geological hazards, urban environmental geology, mining environmental issues, environmental health, and ecosystem integrity. Advanced technologies—such as geophysical and geochemical exploration, remote sensing, geographic information systems (GIS), and big data analytics—have been widely applied in environmental geological research. In parallel, global and regional environmental monitoring networks have been established to support long-term observation and data sharing.

During this stage, China adopted the path of sustainable development and officially designated environmental protection as a fundamental national policy. Against this backdrop, the China Geological Survey under the Ministry of Land and Resources launched the National Land and Resources Survey Program (2000–2012), which was strategically designed to meet the country’s development needs and support resource and environmental protection[18 19]. A series of major environmental geological investigations were carried out, including national assessments of groundwater resources and environmental conditions; urban environmental geological surveys and evaluations; environmental geological investigations of major river basins such as the Yangtze and Yellow Rivers; surveys of the southeastern coastal region and key economic zones; investigations and mitigation planning for land subsidence; early warning and forecasting of geological hazards; assessments of mining-related environmental issues; and investigations of groundwater pollution and its prevention. Based on these efforts, national and regional environmental geological map series were compiled, providing a comprehensive understanding of China's major environmental geological conditions and associated problems. Specialized monitoring networks were established and continuously improved for groundwater, land subsidence, sudden geological disasters, mining geological environments, and soil–water environmental systems[20 21]. These networks significantly enhanced China's monitoring and early warning capabilities. Additionally, various environmental geological information systems were developed, leading to a notable improvement in the country's capacity for geological information services[22 23].

In recent years, in response to major national strategies such as the coordinated development of the Beijing-Tianjin-Hebei region, the Yangtze River Economic Belt, green development along the Belt and Road Initiative, and poverty alleviation in contiguous impoverished areas, the China Geological Survey has adopted a demand-driven and problem-solving approach guided by the principle of "targeting critical needs, addressing major challenges, focusing on strategic goals, and delivering impactful outcomes." A series of initiatives have been launched, including comprehensive geological surveys of key economic zones and urban clusters, groundwater investigations and monitoring, geological hazard surveys and mitigation, assessments of mining environmental conditions, evaluations of resource and environmental carrying capacity with early warning systems, and the development of geological data and information services. These efforts have resulted in the compilation and publication of numerous environmental geological atlases designed to support the planning and development of important economic regions and urban clusters, along with a series of policy recommendation reports. Based on these achievements, several key areas of focus have emerged in China's environmental geological research: urban environmental geology, rational utilization and protection of water resources, geological hazard prevention and mitigation, mining environmental geology, environmental pollution and human health, and sustainable agricultural development[24 25].

3. MAJOR ADVANCES IN ENVIRONMENTAL GEOLOGICAL RESEARCH AT HOME AND ABROAD

Drawing on environmental geological practices both domestically and internationally, this chapter focuses on summarizing current global research progress in key thematic areas, including environmental geological issues related to groundwater development, sudden geological disasters, mining-related environmental geology, soil and water pollution, and the carrying capacity of the geological environment.

3.1 Environmental geological issues related to groundwater development

The protection and rational utilization of water resources has long been a central focus and hot topic in the field of environmental geology. Since the 20th century, countries such as the United States, Japan, China, and nations across Europe and Southeast Asia have significantly increased groundwater extraction. This surge in exploitation has led to a series of serious environmental geological problems, including sharp declines in groundwater levels and quality, land subsidence, and ground fissures In response to these challenges, the focus of groundwater research has gradually shifted from aquifer investigation and water quantity evaluation toward groundwater environmental assessment, protection, and resource management. Currently, the United States leads the world in several key areas, including water resource management, artificial recharge of groundwater reserves, and groundwater pollution prevention and control. Moreover, due to the increasing severity of land subsidence, the United Nations Educational, Scientific and Cultural Organization (UNESCO) established a dedicated Land Subsidence Working Group. This initiative has greatly advanced research in the mechanisms of land subsidence, monitoring and loss assessment, modeling and prediction of subsidence development, as well as prevention and mitigation technologies—contributing significantly to global efforts in combating land subsidence.

Since the 1980s, China has carried out two nationwide assessments of groundwater resources and compiled the Atlas of Groundwater Resources and Environment of China. These efforts evaluated the potential for groundwater exploitation across the country and identified associated environmental geological problems, while also proposing recommendations for the sustainable utilization of groundwater resources. Comprehensive investigations have been conducted on groundwater quality and pollution in key regions and cities across eastern and central China, providing a fundamental understanding of groundwater contamination status and distribution. In addition, national and regional groundwater monitoring programs have been implemented, resulting in the establishment of a four-tier monitoring network at the national, provincial, municipal, and county levels. This network includes more than 20,000 monitoring wells and covers an area of approximately 3.5 million square kilometers. According to data from the end of 2016, groundwater levels remained stable in about half of the monitored areas, while approximately one-third of the areas experienced groundwater level declines. The overall trend in groundwater quality development across the country is also concerning[26] (Fig 1).

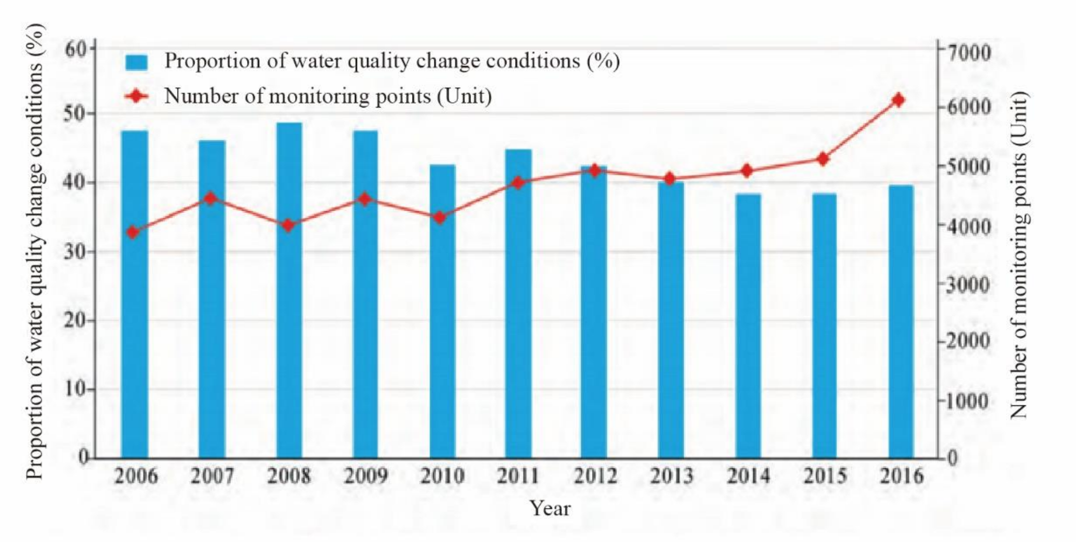

Fig 1. Trends in groundwater quality changes in china over the past decade

Since 2000, China has undertaken extensive investigations and monitoring of land subsidence and ground fissures in key regions such as the Yangtze River Delta, the North China Plain[27 28], the Fenwei Basin, the Jianghan–Dongting Lake Plain, and the Beijing-Tianjin-Hebei area. Specialized monitoring networks have been established in the North China Plain, Yangtze River Delta, and Fenwei Basin. These efforts have supported in-depth studies on the formation mechanisms, modeling and prediction, and monitoring and early warning technologies related to land subsidence and ground fissures. As a result, the spatial distribution and evolutionary patterns of land subsidence have been largely understood, providing critical support for the formulation and implementation of national disaster prevention and mitigation plans, ensuring the geological safety of major urban clusters, and informing the planning and layout of major national infrastructure projects. Currently, international research on land subsidence places greater emphasis on theoretical model development and the application of new monitoring technologies and methodologies. These include interdisciplinary approaches that integrate numerical modeling, fracture mechanics, and damage mechanics; visualization and coupled-function modeling techniques; and advanced decision-support systems for monitoring, early warning, risk classification, and prevention strategies based on 3S technologies—particularly InSAR—and geophysical exploration methods. In these areas, further research and development are still needed in China.

3.2 Research on sudden geological hazards

Sudden geological hazards—primarily including rockfalls, landslides, debris flows, and ground collapses—have long been a central focus of international environmental geological research. Developed countries place significant emphasis on the theoretical frameworks, methodologies, and technologies for landslide disaster prevention and mitigation. Since the 2000s, substantial progress has been made in areas such as the analysis of large-scale landslide disaster mechanisms, high-precision monitoring and early warning technologies, risk assessment methodologies, and the development of prevention and control techniques. In the field of landslide monitoring and early warning, countries such as the United States, Japan, Italy, Germany, and France have reached advanced research levels. Notable achievements have been made in sensor technology, data acquisition, transmission, and analysis. The United States Geological Survey (USGS) has established multiple real-time hydrological monitoring sites on landslides across the country, working in collaboration with meteorological agencies to develop early warning systems. Japan leads the world in landslide observation experiments and predictive model development. Germany has leveraged radar satellite data and interferometric processing technologies to achieve millimeter-level monitoring accuracy, playing a critical role in landslide detection. In recent years, many countries have adopted landslide risk assessment as a key tool for regulating development within high-risk zones. Landslide risk assessment guidelines have been issued to support comprehensive disaster prevention and mitigation management. Regarding natural disaster insurance, countries such as France, Norway, and the United Kingdom have established relatively well-developed catastrophe insurance mechanisms and semi-mandatory insurance systems. However, landslide-specific insurance coverage is not yet widely adopted.

China is among the countries most severely affected by sudden geological hazards (Fig 2), and the challenges of disaster prevention and mitigation remain significant. Since 2000, a series of initiatives have been launched nationwide, including geological hazard assessments for major infrastructure projects, nationwide geological hazard surveys and zoning, the establishment of community-based monitoring and prevention systems, demonstration projects for professional monitoring and early warning in typical high-risk areas, and national geological hazard data collection and early warning efforts. These initiatives have significantly strengthened geological hazard investigation and evaluation, monitoring and early warning, emergency response, and engineering mitigation. A relatively comprehensive geological hazard prevention and control system has been established. National and regional atlases of hazard distribution, susceptibility, and risk assessments have been compiled, providing a foundational understanding of hazard types and spatial development patterns. A nationwide monitoring and early warning system has been implemented, and the National Geological Hazard Information System has been developed. Scientific and technological research on geological disaster prevention and mitigation has made notable progress. Significant achievements have been made in the identification of extremely large landslides, key technologies for emergency response, monitoring and forecasting, and rapid assessment of hazard intensity and risk. A comprehensive research and response system has been established, integrating geological hazard investigation, monitoring and early warning, and prevention and mitigation, supported by dedicated research bases. These efforts have fostered a large pool of technical personnel and established a strong foundation for collaboration among academia, research institutions, and industry, providing solid technical support for national disaster reduction and public safety. In particular, research conducted in the Three Gorges Reservoir area and other mountainous regions prone to geological hazards has led to the development of advanced theories, methodologies, and practical applications, positioning China at the forefront of international research in geological disaster prevention and mitigation.

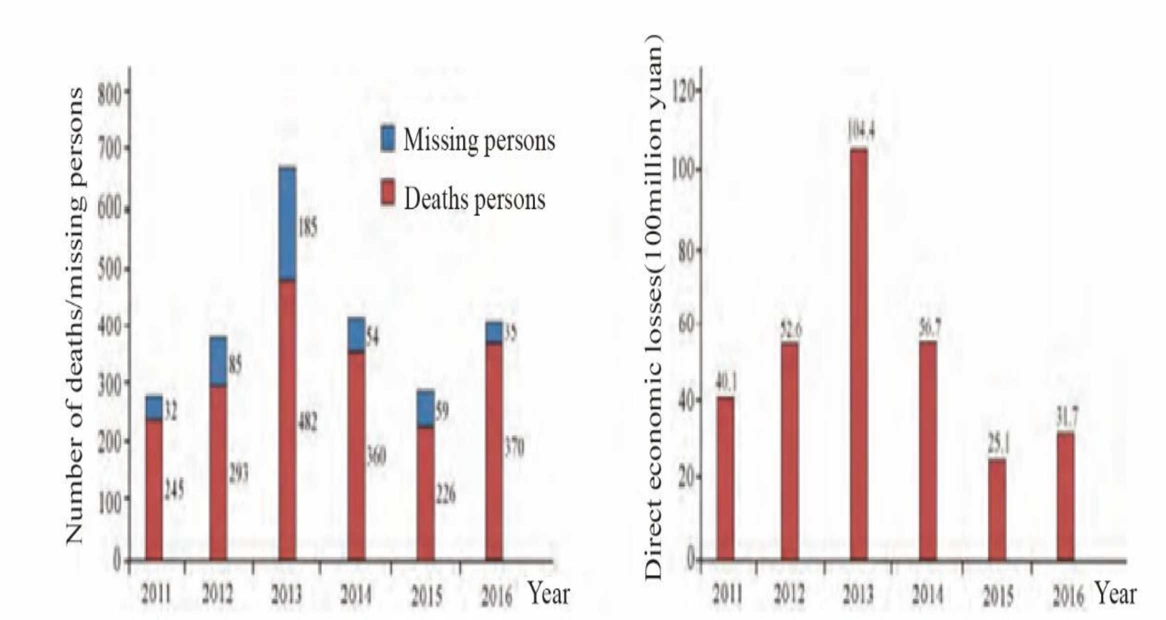

Figure 2. Statistics on fatalities missing persons and economic losses from sudden geological hazards in China (Based on the bulletin of land and resources, 2011–2016)

In the face of increasingly frequent extreme events, geological hazards have become more complex and unpredictable. Disaster chains such as landslide–debris flows and landslide–impulse waves are occurring with greater frequency. Existing theories and technical approaches for geological hazard prevention and mitigation are no longer sufficient to meet the pressing demands of disaster risk reduction. Compared with developed countries, China still faces several challenges in the fundamental research and technological development related to landslide hazard prevention. These gaps are primarily reflected in the following areas: insufficient basic research on the failure mechanisms and evolutionary processes of extremely large landslides; limited application of advanced technologies for rapid landslide identification; inadequate monitoring and early warning technologies under complex environmental conditions; immature spatial prediction and risk assessment techniques for geological disaster chains, with room for improvement in assessment accuracy; underdeveloped commercial insurance mechanisms for geological hazard risk compensation; and the need for further refinement of risk-informed concepts and technical standards in engineering practices for geological hazard control.

3.3 Research on environmental geological issues in mining areas

Research on the environmental geology of mining areas primarily focuses on the interactions and mutual constraints between mineral resource development and the geological environment. The objective is to minimize and mitigate environmental geological problems arising from mining activities while promoting the rational utilization of mineral resources and supporting the sustainable development of the mining industry. As early as the 1970s, mining-developed countries such as the United States, Canada, Australia, and Germany began placing great emphasis on the protection and remediation of mining environments. In the past decade, the integration of mineral resource development and environmental protection has emerged as a key trend in global mining practices.

In China, research on mining-related environmental geology has primarily focused on the formation mechanisms of mining environmental problems, environmental impact assessment, land reclamation and ecological restoration, prevention and control of geological hazards in mining areas, solid waste disposal and treatment, and environmental pollution management[12].Since 2002, two nationwide baseline surveys of mining geological environments have been organized, along with remote sensing investigations and monitoring of key mining areas, and detailed surveys in resource-concentrated regions and ecologically fragile zones of the Qinghai–Tibet Plateau. These efforts have covered over 110,000 mines, providing a preliminary understanding of the current status of China's mining geological environment. Based on the results, national and regional environmental geological map series for mining areas have been compiled, and a comprehensive national database and information system for mining geological environment surveys has been established. Demonstration monitoring zones have been set up in provinces such as Hunan and Hubei to explore monitoring techniques and methodologies for mining environments. These efforts have provided critical decision-making support for the development of national mineral resource plans, the protection and rehabilitation of mining geological environments, and initiatives such as mine site "re-greening" actions.

3.4 Research on soil and water environmental pollution

Research on soil and water environmental pollution primarily focuses on pollution prevention, risk management, and remediation, with the overarching goal of improving environmental quality. Among these, pollution remediation has become a global research frontier, increasingly recognized as critical to protecting human health and ensuring sustainable social development. Since the 1980s, countries such as the United States, Japan, Australia, and members of the European Union have implemented comprehensive soil and water pollution remediation programs. These initiatives encompass site investigation and assessment, remediation plan design, engineering implementation, equipment manufacturing, and the development and application of treatment agents. The United States has undertaken several landmark programs, including underground storage tank cleanup, Superfund site remediation, brownfield redevelopment for contaminated and underutilized land, and pollution cleanup projects under the Department of Defense. These efforts have driven the development of physical, chemical, and biological remediation technologies and equipment, along with a wide range of full-scale restoration projects. Based on this foundation, the U.S. has built a well-established technical system and industrial chain for soil and water pollution remediation, maintaining a leading position globally in this field.

In China, efforts in soil and water pollution remediation started relatively late, and there remains a significant gap in technical expertise and practical experience compared with developed countries in Europe and North America. Since 2000, soil and water remediation has been included in national hightech research and development plans. By the end of 2016, a total of 142 related projects had been launched, including 37 under the 863 Program, 10 under the 973 Program, 56 under the Science and Technology Support Program, and 39 under public welfare sector projects. Over more than a decade of development, China has preliminarily established a technical system, complete sets of equipment, and integrated application platforms for remediating sites contaminated by persistent organic pollutants, petroleum and volatile/semi-volatile organic compounds, and heavy metals. A range of technologies have been developed, such as cement kiln co-disposal, soil washing, thermal desorption, in situ heating, solidification/stabilization, chemical oxidation/reduction, and permeable reactive barriers. These technologies are rapidly evolving toward greater diversity, compatibility, and integrated application. However, the country still lacks comprehensive standards and engineering guidelines for soil and groundwater remediation, and an integrated remediation approach that treats soil and groundwater as a unified system has yet to be fully established. It is worth noting that since 2015, the State Council has successively issued the Action Plan for Water Pollution Prevention and Control and the Action Plan for Soil Pollution Prevention and Control. These landmark policy documents have played a pivotal role in advancing the development of soil and water pollution remediation efforts in China.

3.5 Research on the carrying capacity of the geological environment

The carrying capacity of natural resources and the environment is both a regional and a global issue. As a key indicator for evaluating the coordinated development of the human–environment relationship, it serves as an important metric for assessing regional sustainability. Countries such as the United States and Japan have already applied the theoretical framework of resource and environmental carrying capacity to environmental planning and management, thereby providing guidance for socioeconomic development. Current research, both domestically and internationally, has focused primarily on the carrying capacity of individual elements such as water resources, land resources, and environmental systems. At the same time, notable progress has been made in the theoretical development, methodological innovation, and practical applications related to comprehensive assessments of resource and environmental carrying capacity.

Since the 1990s, China has incorporated the assessment of resource and environmental carrying capacity into major national planning efforts. This began with geological hazard prevention research related to the resettlement of the Three Gorges Reservoir area and continued with comprehensive evaluations of geological safety and soil and water resource security for post-disaster reconstruction planning following the 2008 Wenchuan Earthquake. These efforts marked the first time that carrying capacity assessments were positioned as a foundational component of scientific and technological support, providing critical evidence and technical guidance for resettlement and reconstruction planning. Within this framework, the geological environment has been formally included as a key element in the broader resource and environmental carrying capacity assessment system, and has evolved into a distinct subfield. Geological carrying capacity assessments have since been applied in recovery and reconstruction planning for disaster-affected regions such as Yushu, Zhouqu, and Lushan, as well as in territorial planning for the Bohai Rim region. These applications have provided important scientific and decision-making support for national land-use and socioeconomic development planning. In response to the central government’s call to "establish a monitoring and early warning mechanism for resource and environmental carrying capacity, and impose restrictions in regions where water, soil, environmental capacity, or marine resources are overburdened," the China Geological Survey under the Ministry of Land and Resources launched a series of initiatives. These included nationwide surveys and assessments of resource and environmental carrying capacity, as well as evaluations and early warning systems for geological resource and environmental capacity. As part of these efforts, the Technical Requirements for the Assessment of Resource and Environmental Carrying Capacity (Trial Version) [Document No. 1213, 2016] was issued to guide empirical research at national, provincial, municipal, and county levels. In 2016, the National Development and Reform Commission, together with the Ministry of Land and Resources and 11 other ministries, jointly released the Technical Guidelines for Monitoring and Early Warning of Resource and Environmental Carrying Capacity (Trial) [Document No. 2043, 2016], requiring relevant agencies across the country to implement the guidelines accordingly. China’s research on resource and environmental carrying capacity assessment and early warning has thus entered a stage of full-scale pilot implementation. Currently, cities such as Beijing and Shanghai are actively organizing evaluations of geological disaster susceptibility and geological environmental carrying capacity to support land-use planning and risk-informed development.

4 PROSPECTS FOR ENVIRONMENTAL GEOLOGICAL RESEARCH IN CHINA

At present, China is striving toward the vision of a prosperous, democratic, culturally advanced, harmonious, and beautiful nation. Ecological civilization, regarded as a thousand-year plan for the sustainable development of the Chinese nation, has become a key component of the national agenda in the new era. Without a doubt, environmental geological research now serves as a fundamental pillar for the construction of ecological civilization and the pursuit of sustainable development. In response to pressing national demands—such as strengthening water pollution control, managing and remediating soil contamination, implementing major ecological protection and restoration projects, enhancing wetland conservation and rehabilitation, improving geological disaster prevention and mitigation, and establishing a nature reserve system with national parks as the core—China's environmental geological work is facing new challenges and opportunities. Moving forward, environmental geological research must evolve to support urban development, coordinate the sustainable utilization and management of water resources, enhance comprehensive disaster prevention and mitigation systems, provide technical support for ecological and geological environment management, and advance studies related to the Earth's critical zone. Based on these considerations, the future key research areas and strategic directions for environmental geological work in China are expected to focus on the following aspects:

(1): Urban Environmental Geology

Focus on major challenges and needs associated with the development of key economic zones and urban agglomerations. Conduct comprehensive urban environmental geological surveys, including three-dimensional detection and modeling of subsurface geological structures. Strengthen suitability assessments for engineering construction and the development of underground space, and evaluate the potential and future prospects for the utilization of urban subsurface resources.Establish multi-parameter urban geological environment monitoring networks and develop corresponding evaluation methodologies to assess the comprehensive carrying capacity of resources and the environment. Build urban geological information service platforms, including the development of 3D visual geological models and integrated geological information systems. Based on these platforms, promote the sharing and application of geological information, and explore expression forms and service mechanisms capable of providing precise, full-process support for urban planning, construction, and operational management.

(2): Groundwater Utilization and Protection

Organize and implement a new round of nationwide groundwater resource assessments, evaluating the potential for groundwater development and associated environmental geological issues. Propose strategies and recommendations for the sustainable utilization of groundwater resources. In alignment with national ecological protection goals, carry out hydrogeological and environmental geological investigations in representative regions. Study the evolutionary processes and driving mechanisms of eco-hydrological systems such as wetlands, and examine the relationships between groundwater exploitation and ecological environment regulation. Based on national groundwater monitoring initiatives, improve and expand groundwater monitoring networks at all administrative levels. Enhance automation and technical capacity, increase the diversity and accuracy of monitored parameters, and achieve real-time data transmission and rapid system response.

(3): Integrated Prevention and Mitigation of Geological Hazards

Strengthen investigations and assessments of geological hazards that pose threats to urban areas, major transportation corridors, hydropower facilities, and key mining operations. Conduct research on the disaster-causing mechanisms and spatiotemporal evolution of geological hazards under complex conditions. Develop technologies for dynamic prediction of hazard chains and intelligent, interconnected monitoring and early warning systems. Promote quantitative dynamic risk assessment of landslides based on environmental factor changes, and explore geological hazard insurance mechanisms along with the formulation of relevant technical standards. In parallel, improve geological hazard information networks at all administrative levels, enhance the timeliness and accuracy of hazard assessment and early warning, and establish a more robust emergency response system and mechanism for geological disasters.

(4): Ecological and Environmental Geology

Further advance the investigation and assessment of geological heritage sites. Strengthen research on the formation mechanisms, classification models, and landscape conservation zoning of geological relics, with clear prioritization between protection and development. Promote the application and transformation of research findings on geological heritage. Support the development of geological culture towns and villages, and explore integrated utilization mechanisms that combine geological heritage resources with specialty agricultural products, folk culture, and humanistic landscapes.

(5):Research on Issues Related to the Critical Zone

Enhance comprehensive investigation and monitoring of the Earth's critical zone, with a focus on soil, the vadose zone, and aquifers. Study the transmission of material and energy flows within the critical zone—particularly the migration, transformation, and interactions of chemical substances and pollutants. Promote deep integration of geological science with related disciplines such as geography, oceanography, meteorology, hydrology, and biology, in order to address increasingly complex and interconnected ecological challenges.

5. CONCLUSION

Environmental geological issues have garnered widespread global attention. Based on a brief review of the development of environmental geology as a discipline and an overview of representative environmental geological problems at home and abroad, this paper highlights the major international research advances made over the past decade. In light of China's ecological civilization goals, future directions and key focus areas for environmental geological research have been proposed, including: supporting urban development, coordinating the sustainable utilization and management of water resources, enhancing integrated geological hazard prevention and mitigation, providing technical support for ecological geological environment management, and advancing research related to the Earth's critical zone.

Looking ahead, environmental geological research should continue to center on the interaction between humans and the Earth system, providing precise support for sustainable social development. Greater emphasis should be placed on the systematic protection and management of ecological environments, the integration of interdisciplinary approaches, and the application of new technologies and methods. In alignment with the strategic goals of ecological civilization, the field should continue to expand its research scope, enrich its theoretical frameworks, and deepen its practical applications.

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