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Research Article

Development, hotspots and trend directions of groundwater numerical simulation: A bibliometric and visualization analysis

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Abstract: Groundwater is a vital component of the hydrological cycle and essential for the sustainable development of ecosystems. Numerical simulation methods are key tools for addressing scientific challenges in groundwater research. This study uses bibliometric visualization analysis to examine the progress and trends in groundwater numerical simulation methods. By analyzing literature indexed in the Web of Science database from January 1990 to February 2023, and employing tools such as Citespace and VOSviewer, we assessed publication volume, research institutions and their collaborations, prolific scholars, keyword clustering, and emerging trends. The findings indicate an overall upward trend in both the number of publications and citations concerning groundwater numerical simulations. Since 2010, the number of publications has tripled compared to the total before 2010, underscoring the increasing significance and potential of numerical simulation methods in groundwater science. China, in particular, has shown remarkable growth in this field over the past decade, surpassing the United States, Canada, and Germany. This progress is closely linked to strong national support and active participation from research institutions, especially the contributions from teams at Hohai University, China University of Geosciences, and the University of Science and Technology of China. Collaboration between research teams is primarily seen between China and the United States, with less noticeable cooperation among other countries, resulting in a diverse and dispersed development pattern. Keyword analysis highlights that international research hotspots include groundwater recharge, karst water, geothermal water migration, seawater intrusion, variable density flow, contaminant and solute transport, pollution remediation, and land subsidence. Looking ahead, groundwater numerical simulations are expected to play a more prominent role in areas such as climate change, surface water-groundwater interactions, the impact of groundwater nitrates on the environment and health, submarine groundwater discharge, ecological water use, groundwater management, and risk prevention.

Keywords: Keyword clustering; Visualization analysis; Groundwater numerical simulation; Ecological water use; Groundwater management

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Introduction

Groundwater, as a vital component of water resources, plays an important role in socio-economic development and daily life. However, rapid economic growth has led to numerous negative impacts on groundwater resources due to human activities. Evaluating and managing groundwater resources, as well as preventing groundwater pollution, have become major scientific challenges. With the advancement of computer technology and mathematical theories, numerical simulation methods have emerged as a powerful tool to address these issues (Woods et al. 2003; Xue, 2007).

Groundwater numerical simulation refers to the

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process of using numerical methods based on computer technology to obtain approximate solutions to coupled equations governing groundwater flow and solute transport. This approach aims to determine the spatiotemporal distribution of groundwater flow and the movement and outcomes of solutes in groundwater, considering the interactive effects of physical, chemical, and biological factors (Wang et al. 2019).

In 1856, Henry Darcy published the famous Darcy's Law (Neuman, 1977), laying the foundation for groundwater research. Early researchers used simple electrical analogy models to roughly estimate the convection flow field of groundwater (Taylor, 1953). However, the electrical analogy method could not fundamentally describe and explain the process of solute migration. In the 1950s, Taylor and others developed the hydrodynamic dispersion theory, and around the same time, Vermeulen and his colleagues established expressions to describe adsorption processes (Scheidegger, 1954; Saffman, 1959). These early developments in groundwater theory and simulation methods provided a solid foundation for future numerical simulations.

Since the 1970s, with advancements in computer technology, groundwater numerical simulation has progressed rapidly. Significant achievements have been made in modeling groundwater flow, solute transport, and chemical reactions, as well as their coupling with biological processes (Van Genuchten and Sudicky, 1999; Barry et al. 2002). At the same time, the introduction of three-dimensional flow models, finite element algorithms, and parameter estimation techniques has greatly advanced solute migration simulation (MacKay et al. 1986; LeBlanc et al. 1991; Boggs et al. 1992; Zheng and Gorelick, 2003). Stochastic methods have also been widely applied in simulating flow and solute transport in heterogeneous media. After 35 years of development, groundwater simulation in China has experienced from scratch, from a simple flow model to more complex material and heat transport model, providing scientific support for groundwater resources and groundwater ecological environment management, and has been widely employed in groundwater resources management and environmental protection work.

Bibliometrics is a scientific method that enables the quantitative analysis of all forms of knowledge carriers. Visualization mapping can transform a large volume of textual research papers into intuitive visual representations (Liu, 2023). Through methods such as word frequency analysis, citation analysis, and co-citation analysis, bibliometrics reveals the research content, current hotspots, and future trends in a given field over a specified period of time. Tools like CiteSpace, developed by Professor Chaomei Chen in the US (Chen, 2006), and VOSviewer (Van, 2010), created by CWTS at Leiden University in the Netherlands, play crucial roles as visualization tools in bibliometric research. These two software platforms not only perform quantitative analyses of literature but also offer tools to visualize and analyze the relationships between data or text (Xiao et al. 2013; Orduna-Malea and Costas, 2021). They have been widely and successfully applied across many fields (Leydesdorff and Persson, 2010; Chen, 2012; Zhang, 2017; Bicakci, 2024).

In recent years, the number of publications in the field of groundwater numerical simulation has grown significantly. Solely relying on literature reviews cannot comprehensively reveal the research progress in groundwater numerical simulation from a quantitative perspective.

This paper uses high-quality journal articles published in the field of groundwater pollution research from 1990 to 2023, both domestically and internationally, as the data source. By utilizing Web of Science (WOS), along with CiteSpace and VOSviewer software, a visualization analysis of the literature in the field of groundwater numerical simulation from recent years is conducted. The aim is to uncover research progress, hotspots, and key directions in the international research landscape of groundwater numerical simulation. This analysis is intended to provide valuable insights and guidance for scholars in the field, helping to direct innovation and breakthroughs in groundwater numerical simulation research (Chen and Leydesdorf, 2014).

1 Materials and methods

1.1 Data sources

The research data in the field of groundwater numerical simulation methods were sourced from the Web of Science (WOS) Core Collection database, which reflects the global research trends in this area. The literature search was conducted using thematic keywords such as "numerical modeling", "numerical simulation", "groundwater", "groundwater flow", "modeling", and "solute transport" to retrieve articles published between 1990 and 2023. The document type was limited to "Article". After excluding irrelevant or less relevant studies, a total of 4,615 articles were selected for analysis.

1.2 Research methods

CiteSpace is a software application developed by Professor Chaomei Chen's research team for scientific literature analysis, mining, and visualization (Chen, 2006). VOSviewer, on the other hand, is a tool specifically designed for analyzing and visualizing bibliometric units of knowledge. Its main advantage lies in its excellent graphical presentation capabilities, making it particularly suitable for analyzing large-scale sample data (Zhang et al. 2021; Li et al. 2020; Cao et al. 2021). CiteSpace can generate cluster views, timezone views, and timeline views to display the clustering of keywords. However, CiteSpace has some limitations regarding the display, merging, and organization of keywords, as well as in the subsequent adjustments of complex keyword networks. In contrast, VOSviewer allows for easier operations in merging, deleting, and presenting similar keywords, compensating for the shortcomings of CiteSpace (Yang, 2021; Liu, 2019). This means that both software applications have their respective strengths and can complement each other in bibliometric analysis (Chen, 2014; Fu and Ding, 2019; Martinho, 2019) .

This study is based on bibliometric principles and utilizes CiteSpace software (v.6.2.R7), VOSViewer (v.1.6.20), and Bilbimetrix software to organize and visualize the number of publications, keywords, research authors, and research institutions in the field of groundwater numerical simulation through knowledge mapping. It aims to reveal the development history, research teams, co-occurrence of scholars, and key research focuses and hotspots in this field. The node types selected include "Country", "Institution", "Pruning sliced works", and "Pruning the merged network" as the network pruning methods (Wang et al. 2022; Xie et al. 2021). The node thresholds are set to Top 20 for country cooperation analysis and Top 30 for keyword co-occurrence analysis. In the co-occurrence map, the size of the text or nodes indicates the frequency of occurrence, with different colors representing different years. The lines connecting the nodes illustrate the degree of association between the elements (Guo et al. 2020; Wang et al. 2018; Mao et al. 2018).

2 Results and discussion

2.1 Distribution of publication volume

The volume of publications can provide a clear indication of the changes and activity level within this research field. Fig. 1 created using Bibliometrix software, illustrates the annual publication count from 1990 to 2023. The horizontal axis represents the years, while the vertical axis indicates the number of published papers. Fig. 1 shows that the publication volume in the field of groundwater numerical simulation, as recorded in the WOS database, can be divided into three distinct phases: (1) 1990–2006: During this period, the annual publication count remained below 100, with slow growth; (2) 2007–2015: Publications began to stabilize and increase steadily, with the total number surpassing 200 in 2016; (3) Post-2017: The annual publication volume saw rapid growth. Overall, the publication volume prior to 2010 was three times greater than that in the years before 2010 (Table 1). Notably, the last decade has

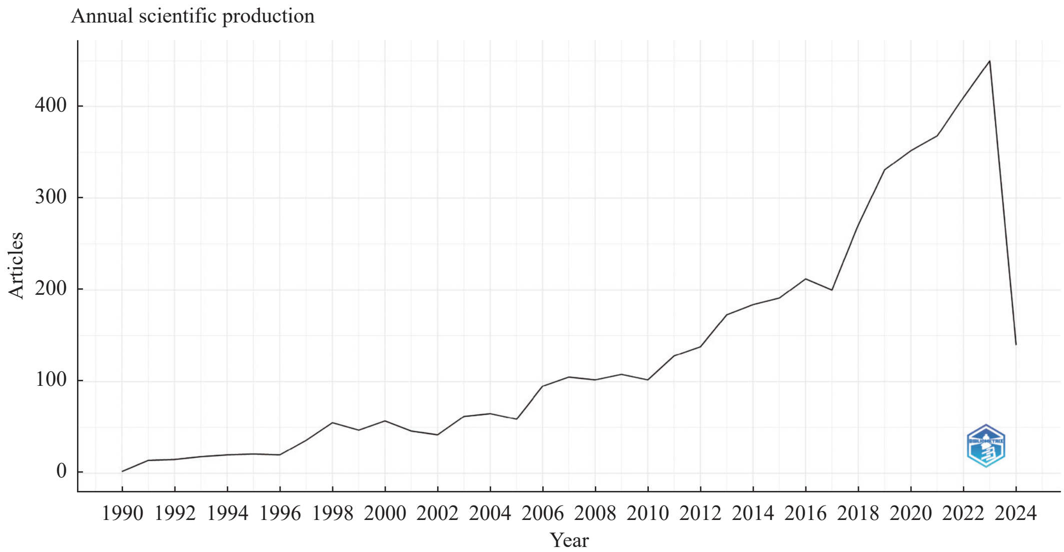

Fig. 1 Publication volume trend from 1990 to 2023

Table 1 Annual publication volume statistics from 1990 to 2023

Year	Number	Year	Number	Year	Number	Year	Number
1990	2	1999	47	2008	102	2017	200
1991	14	2000	57	2009	108	2018	271
1992	15	2001	46	2010	102	2019	331
1993	18	2002	42	2011	128	2020	352
1994	20	2003	62	2012	138	2021	368
1995	21	2004	65	2013	173	2022	410
1996	20	2005	59	2014	185	2023	450
1997	36	2006	95	2015	191		
1998	55	2007	105	2016	212		

witnessed a significant surge in the number of published papers, indicating that groundwater numerical simulation methods are receiving greater attention internationally and are being applied more widely.

2.2 Main research forces

2.2.1 Major research countries

The groundwater issues faced by different countries, along with their comprehensive capabilities, significantly influence the development of groundwater numerical simulation. By conducting a visual analysis of the organized data from Web of Science™, we selected "Country" as the node type and set the time slice to one year, thereby obtaining insights into the research contributions of various countries in the field of groundwater numerical simulation (Table 2, Fig. 2).

Table 2 Top 10 countries by publication volume in the WOS Database (1990–2023)

Country	Documents	Total link strength
China	1,478	498
USA	1,167	619
Canada	392	248
Germany	383	283
Australia	247	246
France	210	156
Italy	207	121
Japan	154	73
Iran	132	83
Switzerland	128	139

Based on the clustering algorithm in VOSviewer, we set the minimum publication threshold to 20. This resulted in 36 countries that have made significant contributions to the field. The top ten countries with the highest publication volumes are China, the United States, Canada, Germany, Australia, France, Italy, Japan, Iran, and Switzerland. Notably, China and the United States account for 57% of the total publications, with China leading in publication volume. This indicates that groundwater issues in China are receiving increasing attention, and its contributions hold a significant position in the field of groundwater numerical simulation. It is noteworthy that the association strength of the United States is higher than that of China, suggesting that there is still room for improvement in the impact of China's research outcomes in the field of groundwater studies.

2.2.2 Main research institutes

The research institutions in a country represent its strategic scientific strength and serve as the most important backdrop for all researchers engaged in scientific inquiries (Guo et al. 2020; Xie et al. 2021). The volume of publications from these institutions not only reflects their academic standards and research capabilities but also signifies their international influence and academic activity. Analyzing institutional collaborations can provide insights into organizations and groups that have made significant contributions in a specific field, laying a solid foundation for future collaborations.

To effectively present the distribution and collaborative relationships among these organizations, we utilized VOSviewer to visualize the organizational collaboration network in this study. We set the minimum publication threshold to 30, resulting in 33 institutions being included in the network (Fig. 3).

The research on groundwater numerical simulation shows an overall upward trend. The volume of publications grew slowly before 2010, but after 2010, the total number of publications increased to more than three times the previous amount. This growth is mainly driven by China and the United States, with the two countries accounting for 57% of the total publications, followed by Canada, Germany, and Australia. The top three journals by

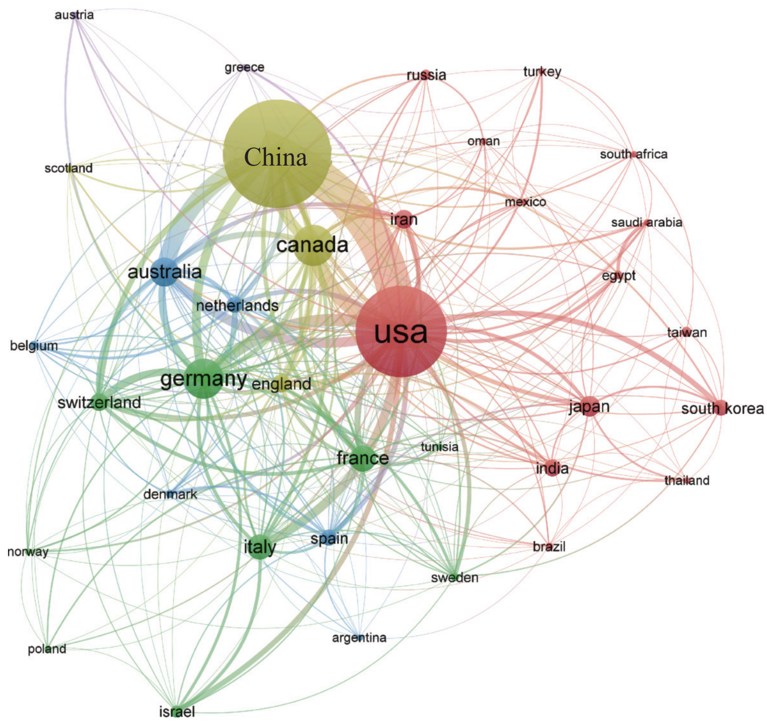

Fig. 2 The country collaboration network involving clustering information

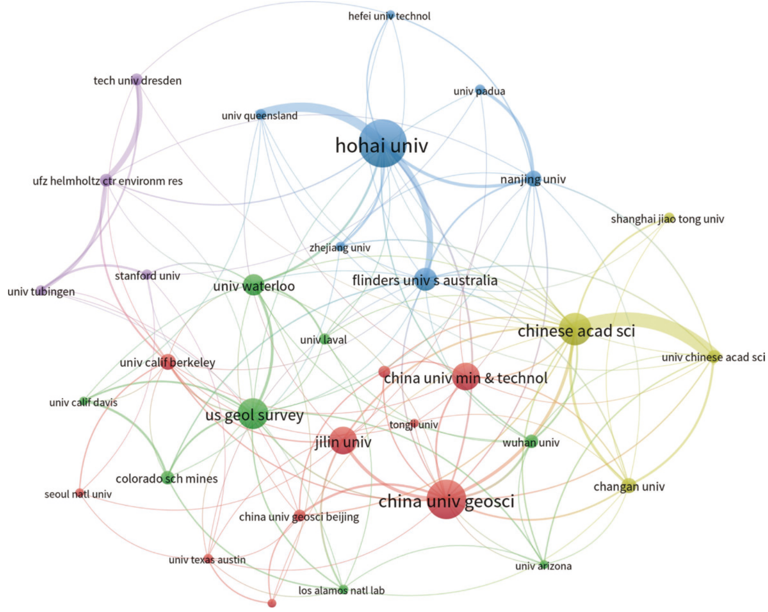

Fig. 3 Institutional cooperation network for research on groundwater numerical simulation

publication volume are Water Resources Research, Journal of Hydrology, and Hydrogeology Journal. It is found that the number of top ten institutions Research institutions are concentrated in China's universities and top research institutes, the US Geological Survey, University of California Berkeley, Flinders University Australia, and University of Waterloo by analyzing the Web of Science™-Core collection database (Table 3, Fig. 3) , showing that these universities and scientific research institutions have played an important role in the research of groundwater numerical method, and also greatly improved the international influence of China in the field of groundwater numerical simulation research.

2.2.3 Major research teams and scholars

The establishment and development of any discipline rely heavily on collaboration among different scholars. The number of publications by a scholar not only reflects their individual academic

Table 3 Top 10 research institutions by publication volume in the WOS Database (1990–2023)

Research Institution	Publications	Citations	Total link strength
Hohai University	168	2,102	64
China University Geoscience	137	2,407	44
Chinese Acadamy Science	114	1,536	79
US geology survey	106	4,636	26
China University of Mining & Technology	97	1,771	13
Jilin University	96	1,221	18
Flinders University Australia	81	2,797	36
University Waterloo	76	2,501	21
Nanjing University	56	849	29
Univercity California Berkeley	56	3,041	19

level but also indicates the research capability and academic activity of their respective teams. As shown in Table 4, the scholars who have made the most significant contributions to the field of groundwater numerical methods are Lu Chunhui (Jing et al. 2023; Zhang et al. 2024; Zhang et al. 2021; Lu et al. 2020), Li Ling (Xu et al. 2024; Jin et al. 2020; Zhang et al. 2016), Wu Jichun (Song et al. 2022; Sun et al. 2021), Simmons Craig T (Ataie-Ashtiani et al. 2020; Mohammad et al. 2018), Werner Adrian D (Yang et al. 2024; Yan et al. 2021), Lu Wenxi (Wang et al.2024; Hou et al. 2021), Li Hailong (Leng et al. 2024; Qu et al. 2020), Xin Pei (Yu et al. 2024; Xin et al. 2018), Datta Bithin (Roy et al. 2021), and Walther Marc (Fang et al. 2021; Stoeckl et al. 2019). In the co-occurrence map of authorship, the relative size of each node represents the frequency of occurrence of that author. Fig. 4 illustrates the contributions of these scholars to the research field through their collaboration network and publication counts (with a threshold set at a minimum publication frequency of 10, including 58 nodes in the network). It is noteworthy that six scholars from China are among the top ten contributors, indicating a strong presence of Chinese scholars in the field of groundwater numerical simulation. In terms of collaboration intensity, international research teams appear to collaborate less, with research developing in a dispersed and diversified manner, and limited cooperation observed between countries.

Table 4 Top ten researchers by publication count in the WOS database (1990–2023)

Author	Publications	Citations	Total link strength
Lu chunhui	35	1,447	55
Li ling	32	757	61
Wu jichun	29	468	29
Simmons craig t.	28	1,613	32
Werner adrian d.	28	1,429	31
Lu wenxi	27	369	10
Li hailong	25	585	30
Xin pei	24	678	44
Datta bithin	22	647	0
Walther marc	21	359	34

2.2.4 Major journal sources

The frequency of the journals can refect the infuence of the journal in its research feld, and high cited journals refect to a certain extent the best source of the research feld (Li et al. 2021; Zhang et al. 2021). Internationally, from 1990 to 2023, research findings on groundwater numerical simulation were primarily published in the top ten journals, including Hydrogeology Journal, Water Resources Research, Journal of Hydrology, Water, and Environmental Earth Sciences (Table 5). These journals are related to geosciences, hydrology, and groundwater, and the publications in these journals account for more than half of the total publication volume.

2.3 Research hotspots

Research hotspots in a particular discipline often represent its frontier studies and can objectively reflect the development trends of that discipline. Identifying these hotspots can assist researchers in planning future investigations.

2.3.1 Keyword clustering analysis

Keywords provide a high-level overview of the content and perspectives of a topic, helping to identify its focus and direction. By analyzing the clustering of keywords in relevant literature, research hotspots can be revealed. To determine the research hotspots in groundwater and ecology over the past 30 years, CiteSpace software was

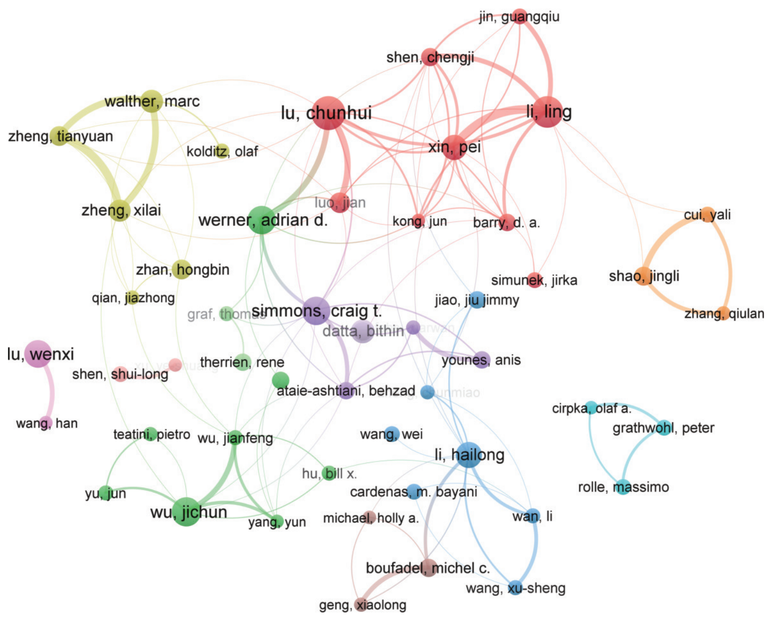

Fig. 4 Publications by authors and author collaboration networks in WOS database

Table 5 Statistics of international publishing institutions, authors and journals of published articles in the field in Web of Science database

Source	Publications	Citations
Hydrogeology Journal	389	7,979
Water Resources Research	354	14,351
Journal of Hydrology	344	9,695
Water	168	1,001
Environmental Earth Sciences	145	2,170
Journal of Contaminant Hydrology	137	4,441
Advances in Water Resources	136	5,005
Science of the Total Environment	53	942
Engineering geology	52	2,130
Transport in Porous Media	50	1,202
Hydrological Processes	48	1,033
Journal of Hydrologic Engineering	48	1,170

used to analyze keywords from articles and publications in the Web of Science (WOS) database from 1990 to 2023.

Based on the co-occurrence knowledge map of keywords obtained from the Web of Science Core Collection database, synonyms or closely related keywords were filtered, and less relevant terms were removed. This led to a keyword clustering analysis, resulting in the top ten keyword clusters (Fig. 5).

In this analysis, "Modularity" refers to the cluster module value (Q value), where a Q value greater than 0.3 is generally considered indicative of a significant clustering structure. "Silhouette" refers to the average silhouette value (S value), with S values greater than 0.5 considered reasonable and those above 0.7 indicating convincing

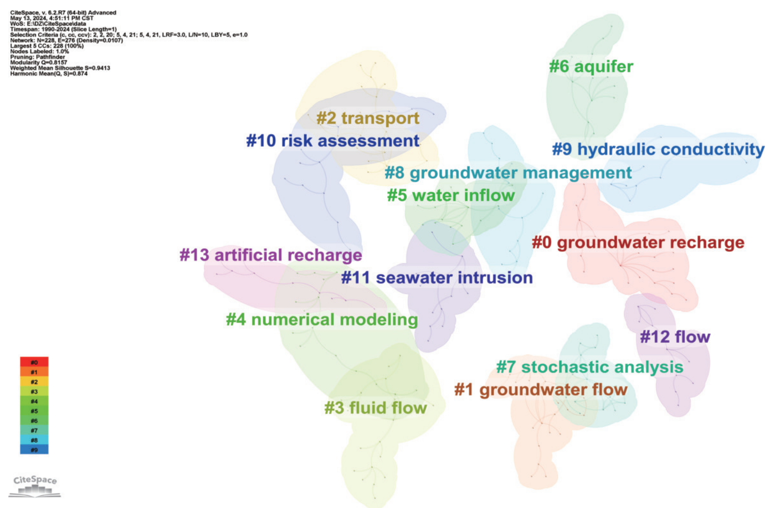

Fig. 5 Keyword clustering on groundwater numerical simulation in WOS database

clustering (Chen, 2017).

The data shows that 14 clusters were formed in the WOS™ database: #0 groundwater recharge, #1 groundwater flow, #2 transport, #3 fluid flow, #4 numerical modeling, #5 water inflow, #6 aquifer, #7 stochastic analysis, #8 groundwater management, #9 hydraulic conductivity, #10 risk assessment, #11 seawater intrusion, and #12 flow. The results of the 14 cluster categories are illustrated in Fig. 5, with a modularity (Q value) of 0.8157 and a silhouette (S value) of 0.9413.

2.3.2 High-frequency keywords

The frequency of keywords indicates the research hotspots within a specific discipline (Liu et al. 2019). Therefore, sorting keywords by frequency can enhance our understanding of the research field. Analyzing high-frequency keywords helps infer the main research directions, methodologies, and current trends. In this study, VOSviewer software was employed to conduct a co-occurrence analysis of keywords from articles related to groundwater numerical simulation methods published in the WOS database from 1990 to 2023, extracting the top 50 high-frequency keywords. In this co-occurrence network, each node represents a keyword. The larger the node, the higher the frequency of that keyword's occurrence. The distance between keywords reflects their relationships; a shorter distance between two nodes indicates a stronger correlation between those two keywords. The co-occurrence frequency was set to 15, resulting in 118 nodes included in the network. The results are shown in Table 6 and Fig. 6.

Table 6 presents the top 50 high-frequency keywords, highlighting the main research hotspots in the field from 1990 to 2023. The primary research subjects include groundwater, surface water, seawater, and the unsaturated zone aquifers. Key research topics encompass the characterization of mathematical models, parameter processing, model calibration, machine learning, the transport of water and pollutants in both homogeneous and heterogeneous aquifers and fractured rocks, seawater intrusion, geothermal water simulation,

Table 6 High frequency keywords in WOS database (1990–2023)

Rank	Keyword	Occurrences	Rank	Keyword	Occurrences
1	Numerical modeling	990	26	Groundwater modeling	41
2	Numerical simulation	598	27	Contamination	40
3	Groundwater	390	28	Karst	38
4	Groundwater flow	186	29	Reactive transport	36
5	Coastal aquifer	111	30	Feflow	35
6	Seawater intrusion	108	31	Hydrogeology	35
7	Modeling	101	32	Unsaturated zone	35
8	Solute transport	99	33	Conceptual models	34
9	Groundwater management	84	34	Laboratory experiments	34
10	Modflow	80	35	Vadose zone	33
11	Heterogeneity	78	36	Artificial recharge	32
12	Groundwater recharge	68	37	Subsidence	31
13	Saltwater intrusion	66	38	Groundwater level	30
14	Analytical solution	62	39	Groundwater/surface-water relations	30
15	Porous media	61	40	Uncertainty	30
16	USA	54	41	Aquifer	29
17	Hydraulic conductivity	53	42	Permeability	29
18	Contaminant transport	52	43	Remediation	29
19	Climate change	50	44	Simulation	27
20	Fractured rocks	50	45	Surrogate model	27
21	Land subsidence	47	46	Transport	27
22	Sensitivity analysis	47	47	Dispersion	26
23	Groundwater contamination	46	48	Optimization	25
24	Submarine groundwater discharge	46	49	Recharge	25
25	China	41	50	Seepage	25

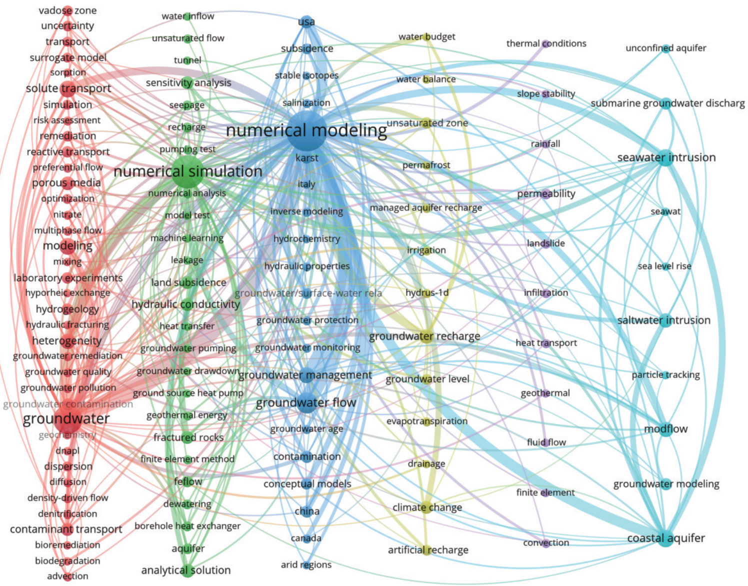

Fig. 6 Co-occurrence keyword network

water resource protection and management, interactions between surface and groundwater, as well as canal leakage studies. The focus areas for this research are primarily in China and the United States. This field integrates various disciplines, including hydrogeology, water resources, hydrogeochemistry, hydraulic engineering, ecology, and geography.

2.3.3 Characteristics of research hotspots

(1) Expansion of research scope and diversification of research models and perspectives

Groundwater numerical simulation has evolved from non-existence to a wide array of models, progressing from simple flow models to more complex models of solute and heat transport. The primary models include various constant-coefficient and variable-coefficient flow models (Xue et al. 2007), groundwater pollution models (Lin et al. 1985; Xue et al. 1997), variable-density flow models (for seawater intrusion) (Xue et al. 1995; Sun et al. 2023), high-concentration (greater than 100–200 g/L) saline/brine intrusion models, groundwater solute transport models, large-scale land subsidence models (covering an area of over 17,000 km^2), heat transport and aquifer storage models, groundwater resource management models, optimal layout models for wells and channels, various seepage models for dams, channel seepage models, and joint evaluation and scheduling models for groundwater-surface water systems.

Today, groundwater numerical simulation has evolved from focusing on singular research objects and simple variations in water levels and quantities to studying the interactions between different water bodies and the entire ecological water cycle system. With the emergence of new technologies and theoretical methods, the research content of groundwater numerical simulation has deepened, the technical means of simulation have become more mature, and the accuracy of simulations has gradually improved (Yu et al. 2024; Yang et al. 2022; Yan et al. 2021; Yang et al. 2019; Wang et al. 2018).

(2) Policy direction drives the evolution of hot research areas

Keyword analysis indicates that China and the United States are the countries where groundwater numerical simulation is most mature and widely applied. In the related research of these two countries, research themes are closely linked to national policies. In 2019, China proposed to strengthen ecological civilization construction to enhance groundwater management, ensure groundwater quality, and promote sustainable use. This initiative aims to transform the traditional production and consumption models characterized by "mass production, mass consumption, and mass emissions," ensuring that resources, production, and consumption are aligned and compatible. The policy places significant emphasis on the rational use of land resources, as well as issues related to water resources, water ecology, and the water environment. The National Academy of Sciences (NASA) in the United States released a research report titled "*Priority Research Directions for Future Water Resource Science in the US,*" which identifies the main challenges facing water resource science over the next 25 years (Petersen et al. 2018; National Academics of Sciences, Engineering and Medicine, 2018). Recent research in groundwater numerical simulation has increasingly focused on groundwater recharge, risk prevention, seawater intrusion, contaminant transport, and geochemical cycles. There has also been a growing emphasis on sponge city construction, the South-to-North Water Diversion Project, watershed ecological environments, and the impacts of human activities and land use.

2.4 Research frontiers and trends

Research frontiers typically refer to the research themes that hold the most potential for future academic development.

2.4.1 Keyword co-occurrence cluster analysis

Using the visualization function of CiteSpace, we conducted a timeline view analysis of keywords from 1990 to 2024. The timeline view of this research is shown in Fig. 7. The analysis of keywords reveals the top 14 clusters. Keywords within the same cluster are displayed on the same timeline according to their occurrence time. The keyword-timeline view intuitively shows the origins and development of the research. As indicated in Fig. 8, since 2010, especially after 2015, important research topics have included groundwater recharge, carbon, thermal conditions, performance, climate change, numerical modeling, seepage, submarine groundwater discharge, artificial recharge, and groundwater management.

2.4.2 Keyword burst detection

Research frontiers refer to the scientific problems or themes that emerge within a specific period from a collection of reference literature. They represent the most advanced and promising hotspots in their respective research fields (Chen, 2016). Therefore, the keyword burst detection knowledge graph can be used to track the frontiers of groundwater numerical simulation research.

Using CiteSpace software, we identified keywords that experienced a sudden increase within a short time frame and employed burst detection analysis to observe rapidly growing topics, thereby understanding the changes in these topics in recent years. This study constructed a keyword co-occurrence network from 1990 to 2024, detecting a total of 118 burst keywords. The top 30 keywords are shown in Fig. 8. These 30 keywords represent current and future research trends in these fields.

In this graph, the year indicates the first occurrence of the keyword, the strength represents the intensity of the burst, the start year denotes when the burst began, and the end year indicates when the burst ended. Fig. 8 illustrates the evolution of research hotspots in groundwater numerical simulation over different periods, as detailed below:

(1) Prior to 2003, research hotspots were largely concentrated in areas such as stochastic analysis, sand aquifer, natural gradient experiments, heterogeneous porous media, groundwater flow, dispersion, solute transport, spatial variability, unsaturated flow, transport, finite element methods, and convection. Among these, research on solute transport, groundwater flow, and dispersion has been a focus for as long as 20 years, marking them as key

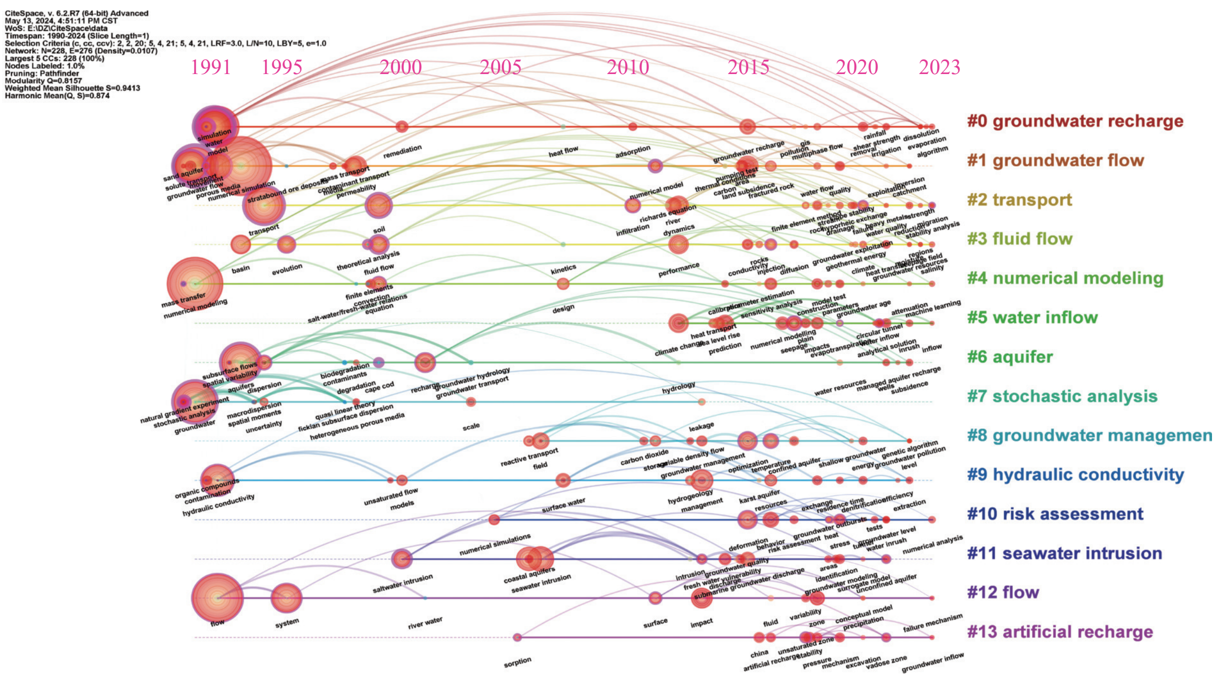

Fig. 7 Timeline view of keywords on groundwater numerical simulation

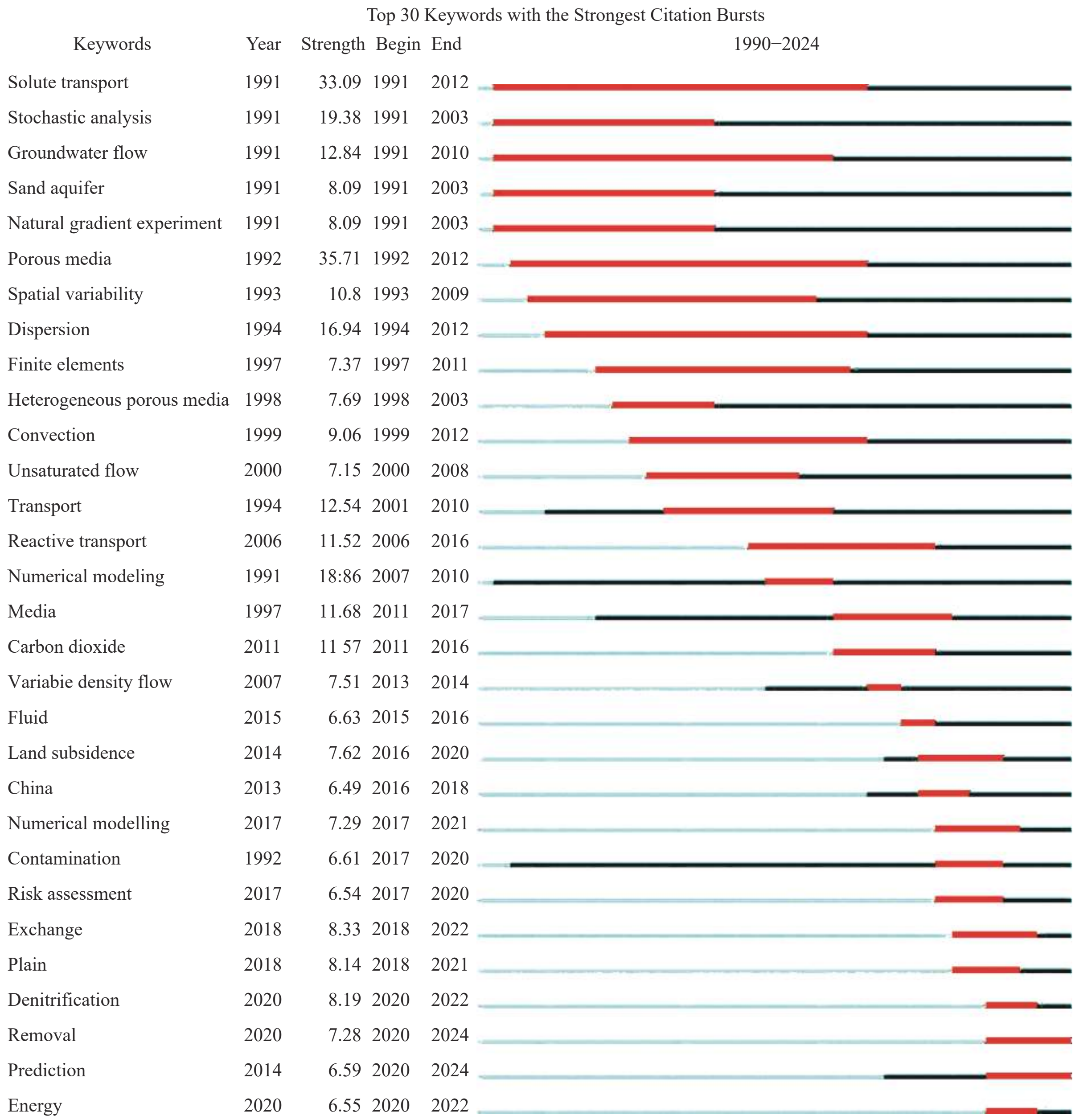

Fig. 8 Top 30 keywords with the strongest citation bursts from 1990 to 2024

areas of interest before 2010.

(2) From 2010 to 2017, as countries increased their focus on ecological environments and soil and water quality, groundwater numerical modeling methods began to emphasize areas such as carbon dioxide, land subsidence, numerical modeling, variable density flow, and risk assessment, with a burst intensity greater than 7. This indicates that carbon dioxide reduction, variable density flow numerical modeling, and pollution prevention have become focal points. Notably, after 2016, land subsidence and risk assessment continued to attract sustained attention from researchers and are expected to develop further in the future.

(3) In the past five years, from 2018 to 2024, research frontiers have included topics such as exchange, energy, removal, and prediction, which have garnered significant attention from scholars and have become the latest research themes.

2.4.3 Future research directions

This paper constructs trend themes based on keywords in recent years using VOSViewer (Fig. 9). Fig. 9 shows that in recent years, the research themes have increasingly focused on the prediction and identification of system model optimization and model characterization, which are fundamental to numerical simulation. Therefore, model test, machine learning, settlement, and analytical solution are directions for improving numerical simulation methods in the past three years. Addi-

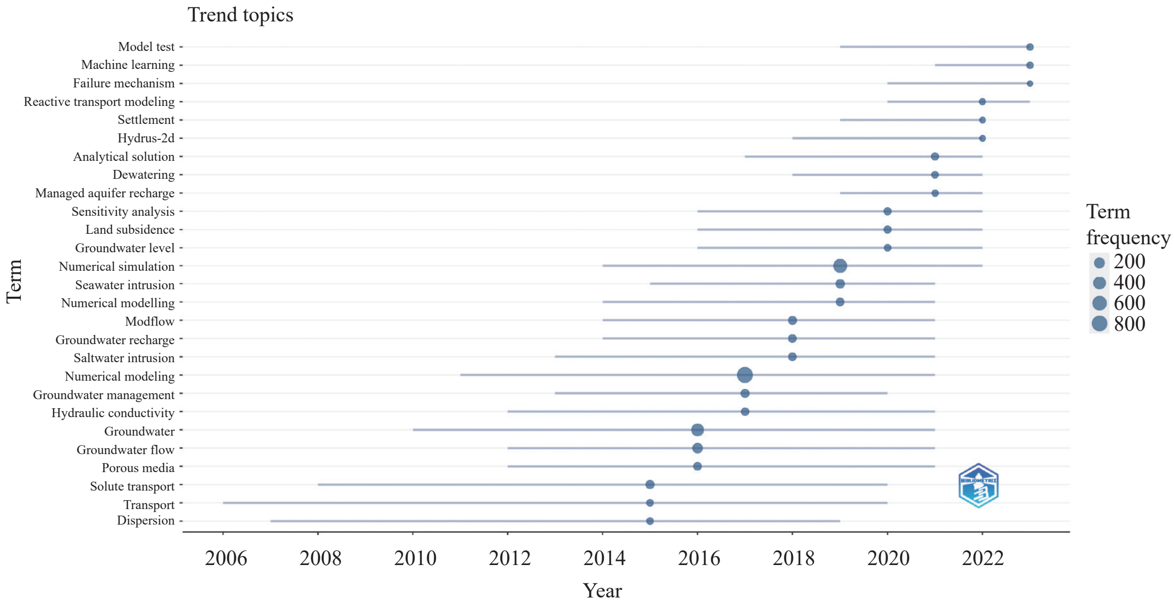

Fig. 9 Trend topics on groundwater numerical simulation

tionally, in terms of research subjects, groundwater will remain a continuous focus, with related research themes such as sensitivity analysis, managed aquifer recharge, land subsidence, and saltwater intrusion ranking among the top five, indicating they will become major research directions in the future.

In summary, groundwater numerical simulation methods have evolved beyond being merely important techniques in groundwater science; they now facilitate interdisciplinary research. By integrating hydrology with geology, geochemistry, ecology, disaster science, geothermal studies, mathematics, and other disciplines, these methods are increasingly shifting towards a multi-element-driven approach that encompasses various temporal and spatial processes. The research focus has transitioned from terrestrial ecosystems to marine ecosystems, placing greater emphasis on the interactions between human activities and groundwater environments, as well as on the modeling and prediction of various environmental issues arising from groundwater exploitation. With improvements in numerical simulation optimization and the accuracy of geological models, the research directions are expected to expand further, potentially entering a more mature stage of development.

3 Conclusions and prospect

(1) The research on groundwater numerical simulation shows an overall upward trend. The volume of publications grew slowly before 2010, but after 2010, the total number of publications increased to more than three times the previous amount. This growth is mainly driven by China and the United States, with the two countries accounting for 57% of the total publications, followed by Canada, Germany, and Australia. The top three journals by publication volume are Water Resources Research, Journal of Hydrology, and Hydrogeology Journal. Research institutions are concentrated in China's universities and top research institutes (such as Hohai University, China University of Geosciences, Chinese Academy of Sciences, Nanjing University) as well as the US Geological Survey, University of California, Berkeley, and University of Waterloo. In this field, the teams of Simmons and Werner show significant advantages. Chinese researchers, particularly Lu Chunhui, Li Ling, and Wu Jichun's teams, have high publication volumes, enhancing China's international influence in this area. However, collaboration among Chinese scholars and between international research teams is relatively scattered and not particularly significant.

(2) The research hotspots in groundwater numerical simulation are continually evolving. Prior to 2010, the focus was primarily on the characterization of mathematical models, parameter processing, and model calibration, with topics such as solute transport, groundwater flow, dispersion, porous media, and seepage being prominent research areas. From 2010 to 2017, the hotspots shifted towards areas like carbon dioxide, land subsidence, numerical modeling, variable density flow, and risk assessment, indicating that carbon dioxide reduction, variable density flow numerical simulations, and soil and water environmental pollution prevention became key priorities. In

recent years, topics such as land subsidence, risk assessment, exchange, energy, removal, prediction, and machine learning have garnered significant attention from researchers, emerging as the latest research themes. This trend reflects a growing emphasis on improving model accuracy in groundwater numerical simulation research, with research content closely aligned with policy directives and increasingly applied to predicting different trends and mitigating risks.

(3) Today, groundwater numerical simulation is increasingly intersecting with disciplines such as mathematics, chemistry, and geophysical exploration. With advancements in technology, the future research directions in groundwater numerical simulation include, first, the optimization of the simulation performance of the models themselves, and second, providing solutions to issues related to groundwater environments and human activities. Topics such as model testing, settlement, analytical solutions, sensitivity analysis, managed aquifer recharge, land subsidence, and saltwater intrusion will become major areas of research focus in the future.

It is worth noting that large-scale watershed modeling still has shortcomings in process understanding, mathematical representation, scale transformation, and the coupling mechanisms of water flow cycles. In the future, greater emphasis should be placed on experimental research of fundamental theories and studies of specific geological conditions. There should be an enhancement of large-scale field experiments to provide the necessary support for groundwater cycling and the sustainable use of groundwater resources.

Overall, the future of groundwater numerical simulation will adopt a more diversified perspective. By comprehensively considering the relationship between human activities and the groundwater environment, it aims to enhance the capacity to address groundwater resource challenges through in-depth studies on groundwater interactions with land use, environmental climate, and hydrothermal characteristic parameters. This includes innovations in climate change simulation and prediction, hydrological and water quality changes in typical watersheds, coupling information systems with groundwater flow numerical models, and the integration of surface water and groundwater.

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