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Research hotspots and trends of groundwater and ecology studies: Based on a bibliometric approach

Jun Liu[1,2], Yan-pei Cheng[1,2*], Feng-e Zhang[3*], Xue-ru Wen[1,2], Liu Yang[1,2]

[1] *Institute of Hydrogeology and Environmental Geology, Chinese Academy of Geological Sciences, Shijiazhuang* 050061, *China.*
[2] *Key Laboratory of Groundwater Sciences and Engineering, Ministry of Natural Resources, Zhengding* 050803, *Hebei, China.*
[3] *Comprehensive Survey and Management Center for Natural Resources, China Geological Survey, Beijing* 10055, *China.*

Abstract: Groundwater, as a critical component of the hydrological cycle, is essential for sustainable ecosystem development. To clarify the current status of domestic and overseas research, and to identify hotspots, frontier and future trends of groundwater and ecology research, this study utilizes bibliometric methods and CiteSpace software to examine relevant published articles in the Web of Science (WOS) and CNKI databases from 1978 to 2022. Specifically, this study analyzes (1) the annual number of published papers; (2) research institutions; (3) keywords; and (4) evolution of research hotspots. The findings reveal that the United States, China, and Germany are the top three countries in groundwater and ecology research. International research hotspots mainly focus on microbial ecology, climate change, groundwater-surface water interactions in the hyporheic zone, biodiversity, and submarine groundwater discharge, while domestic research hotspots mainly focus on ecological water conveyance, ecological flow, groundwater development and utilization, groundwater pollution, and groundwater and ecological protection. Both domestic and international research hotspots exhibit interdisciplinary features with diverse research objects and assessment methods. Future research in this area is expected to focus on topics such as contamination, groundwater quality, framework, mechanism, spatial distribution, and dissolved organic matter. Additionally, the study of ecological recharge, ecological flow, ecological protection, water intake and use will continue to be the hot topics domestically.

Keywords: Ecological assessment; Keywords clustering; Knowledge graphing; Ecological security; Ecological restoration

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Introduction

Research on groundwater and ecology is crucial for promoting the sustainable development of groundwater resources and the ecosystem, as well as for promoting social and economic development and improving people's lives. Groundwater is closely related to ecological environmental issues and is one of the most important factors controlling the ecological environment (Xu et al. 2016). Under the background of ecological civilization construction, research on groundwater and ecology research carries significant theoretical importance for the coordinated development of humans and nature. The study of groundwater and ecology is a broad field covering topics such as groundwater resources, groundwater environment, groundwater ecology, groundwater pollution, biodiversity, the interaction of different water bodies in the hyporheic zone, microbial mechanism, and evolution patterns and ecological effects of groundwater under changing environments, etc. The core research is to investigate the relationship between the survival and development of biology and groundwater. From the biological point, the groundwater environment is the essential habitat for plants, animals and microorganisms, where they can absorb the nutrients; from the hydrogeological point, the biota characteristics of aquifers are the best indicators of hydro-geochemical processes

*Corresponding author: Yan-pei Cheng, Feng-e Zhang, *E-mail address*: yanpeicheng@tom.com feng_ezhang@163.com

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(Long et al. 2012). Over the past 20 years, global climate change and human activities have posed a great threat to the ecological and groundwater environment, resulting in a shortage of groundwater resources and environmental crisis. Governments have funded research on groundwater and ecology, leading to a sharp increase in the number of published articles in this field globally. At present, international studies mainly focus on (1) the action of microorganisms (Flynn et al. 2008; Maamar et al. 2015; Beganskas et al. 2018; Fillinger et al. 2021; Griebler et al. 2022); (2) groundwater-surface water interaction in the hyporheic zone (Sophocleous, 2002; Hayashi and Rosenberry, 2002; Kalbus et al. 2006; Conant et al. 2019); (3) biodiversity (Griebler and Lueders, 2009; Danielopol et al. 2000; Boulton et al. 2008); (4) the response of groundwater and ecosystem in changing environments (Dams, 2012; Crosbie et al. 2013; Bussi et al. 2018; Epting et al. 2022); (5) groundwater resource evaluation based on ecological consideration and (6) groundwater-dependent ecosystem (Griebler et al. 2010; Korbel and Hose, 2011; Bertrand et al. 2012; Glanville et al. 2016; Voisin et al. 2020; Majola et al. 2022). In China, research in this field mainly focus on solving practical problem, including (1) regional water cycle evolution (Huan et al. 2011; Zhu et al. 2014; Yin et al. 2021; Chen et al. 2022); (2) surface water-groundwater environment interaction (Wu et al. 2005; Wang et al. 2007; Ling et al. 2011; Ma et al. 2013; Zhu et al. 2017); (3) groundwater ecological effects (Ma et al. 2002; Xu et al. 2016; Wang et al. 2018; Wang et al. 2019); (4) the control and prevention of groundwater pollution (Luo, 2008; Xue and Zhang, 2009; Teng et al. 2012; Zhang et al. 2014; Xi et al. 2018); (5) ecological remediation of groundwater pollution (Zhang et al. 2004; Zhou et al. 2021; Li et al. 2021; Fei et al. 2022); (6) groundwater microbial effects (Yang et al. 2011; He and Chen. 2015; Huang et al. 2021; Zhang et al. 2022), especially about the interaction between groundwater and ecosystems in typical areas and river basins (Wang et al. 2011; Xu and Zhang, 2018; Zhang and Yong, 2018; Han et al. 2021; Cui et al. 2021). These studies provide theoretical and technical support for understanding the current situation of groundwater and the ecosystem, promoting the restoration of the ecosystem and improving its function, and ensuring the sustainable development of groundwater and ecology. The summary of these research findings can help to reveal hotspots and difficult issues in this field, leading to the research trends and the development of this academic discipline.

In the era of big data, scholars face the challenge of staying up-to-date with the latest research development trend and difficult issues in their field. Identifying research frontiers, hot spots, veins, and scientific issues in related fields can be particularly challenging (Yang and Cheng, 2017). Bibliometric is a method that uses mathematical and statistical methods to analyze the quantitative relationships presented in different references, and reveal the characteristics and trend of a certain discipline's development. It helps researchers to work on massive datasets in a more efficient way. However, traditional bibliometric methods involve a lot of calculation and mapping work, making it difficult to handle massive amounts of data. In contrast, scientific knowledge graphing is a method of scientific data mining that visualize the structure, regularity and distribution of scientific knowledge. It can simplify the research process and improves analysis efficiency, making it a valuable tool for academic research.

Among a lot of bibliometric software, CiteSpace is a powerful tool to identify scientific trends and developments in a certain field by analyzing the potential contents contained in references. With its visualization function, CiteSpace can present the dynamic evolution, development trend, research progress, frontier issues, and hotspots of a certain field to researchers in a clear and concise manner. One of the advantages of CiteSpace is that it integrates visualization, bibliometric methods and data mining techniques. The software has many powerful functions and can analyze both Chinese and English references (Xiong et al. 2022; Li et al. 2022; Wang et al. 2022). Currently, it is more widely used in different field of domestic references analysis (Wei et al. 2019; Zhang et al. 2020; Guo et al. 2020; Cao and Lu, 2021; Dong et al. 2022; Zhuang et al. 2022). However, there have been only a few domestic studies that investigate groundwater and ecology by using CiteSpace software. Only few relevant studies have been published. For example, Xie et al. (2021) analyzed the research trend of groundwater pollution studies by using this method. Liu et al. (2022) made an analysis of relevant references on surface water-groundwater interaction with CiteSpace. They stated the relevant findings in the field of surface water-groundwater interaction and derived the current research hotspots and future directions. Wang et al. (2022) used this method to discuss various researches on water resource utilization efficiency and identify hotspots and future study trends. He and Yang (2022) used CiteSpace software to visualize and analyze the current situation and hotspots of ecological environmental protection research in the Yellow River basin and introduced hotspot issues and key regions.

Based on the above analysis, this paper aims to use a bibliometric approach to examine the research on groundwater and ecology over the past 40 years, and then employ CiteSpace software to summarize the research progress, core directions and hotspots in this field at both domestical and international levels over the past 20 years. The objectives of the paper are to (1) identify the key issues and technologies used in this field; (2) provide a theoretical basis for maintaining regional ecological security; and (3) promote the sustainable use of groundwater resources and ecosystem development.

1 Data and methods

This study utilized the Web of Science (WOS) core collection database and CNKI database to collect references from 1978–2022. The keywords of "groundwater" and "ecosystems" were used for WOS, while "groundwater" & "ecology" was used for the CNKI database. A total of 9 382 English articles and 21 347 Chinese articles related to the above given keywords were found in WOS and CNKI databases during the mentioned period. The collected articles were then analyzed citespace to determine the number of annual publications, research countries, and research institutions. The software was then used to perform keyword clustering and burstness analysis to identify the current research focuses, hotspot evolutions, and possible future research trends in groundwater and ecology studies. The CiteSpace version used for data processing is version 6.1.R6.

2 Results and discussion

2.1 Time distribution feature of published articles

The number of published article over time is an important indicator to reveal the development trends in a field. Table 1 shows the results of the statistical analysis of the annual quantity of published papers related to groundwater and ecology exported from WOS and CNKI database from 1978–2022. By sorting the data in chronological order, the variation trend of the annual number of published papers in the two databases can be inferred. The details are shown in Fig. 1.

In Fig. 1, two major trends of the yearly numbers of relevant published papers in WOS are shown: (1) the number of publications increased at a slow and steady state during 1978–1999; (2) the number of published articles increased from about 100 in 2000 to more than 1 000 in 2021, indicating expanding attention in related research domains. In contrast, the trend of the number of related published articles in CNKI database can be divided into four stages: (1) the annual number of published articles

Table 1 Yearly numbers of published papers on groundwater and ecology exported from WOS and CNKI database

Year	Number of papers (WOS)	Number of papers (CNKI)	Year	Number of papers(WOS)	Number of papers(CNKI)	Year	Number of papers(WOS)	Number of papers (CNKI)
2022	321	446	2007	176	1 037	1992	37	24
2021	1 007	1 454	2006	183	937	1991	25	31
2020	854	1 346	2005	156	807	1990	5	24
2019	767	1 249	2004	117	642	1989	9	11
2018	693	1 215	2003	141	484	1988	1	6
2017	629	1 234	2002	102	292	1987	1	15
2016	560	1 255	2001	100	230	1986	1	9
2015	557	1 011	2000	99	156	1985	-	13
2014	462	1 055	1999	90	52	1984	1	14
2013	377	1 104	1998	110	39	1983	1	6
2012	337	989	1997	75	51	1982	-	5
2011	370	977	1996	60	42	1981	-	5
2010	276	1 035	1995	94	32	1980	1	-
2009	262	949	1994	56	21	1979	-	2
2008	220	1 014	1993	48	25	1978	1	2

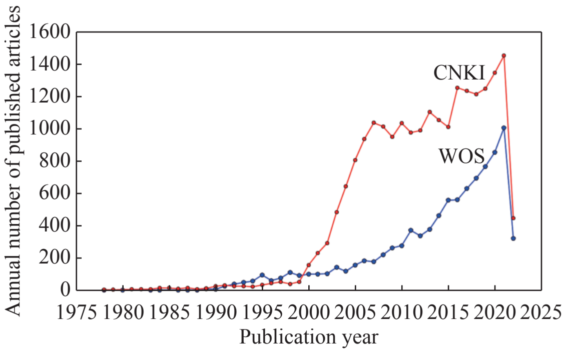

Fig. 1 Annual distribution of articles included in WOS and CNKI database (1978–2022)

remained at slow growth rate with an annual total of fewer than 50 articles during 1978–1999; (2) the annual number of publications showed an exponential increase from 150 in 2000 to more than 1 000 in 2007; (3) from 2008 to 2015, the annual publication number oscillated around 1 000; (4) another exponential growth from 2016 up to the present. Until 2020, more than 1 400 papers were published in the CNKI database. These data show that the study of groundwater and ecology is a main focus in research both domestically and internationally. Comparing the data on the annual number of publications in these two databases, it can be found that the substantial increase in the number of published papers appeared from 2000, and foreign studies in this area began earlier than those in China. However, since 2001, the total number of related publications in CNKI database has already exceeded the number of articles published in the WOS database, with more than 150 publications in 2001. This indicates that Chinese scholars began to pay more attention to this research topic. To date, the number of publications in CNKI database has far exceeded the number of publications in WOS.

2.2 Major research teams

2.2.1 Major research countries

Based on data from the WOS database, the top 10 countries with most publications in the field of groundwater and ecology are the USA, China, Germany, Australia, Canada, England, France, the Netherlands, Spain and Italy. The USA and China have published more than 1 000 publications, and the top three countries together account for 59.4% of the total publications (Table 2).

Table 2 Top 10 countries in number of published articles in WOS and CNKI database

NO	Country	Number of articles	Percentage
1	USA	3 135	33.4%
2	China	1 496	15.9%
3	Germany	947	10.1%
4	Australia	914	9.7%
5	Canada	632	6.7%
6	England	526	5.6%
7	France	475	5.1%
8	Netherlands	457	4.9%
9	Spain	421	4.5%
10	Italy	380	4.1%

2.2.2 Major research institutions

The top research institutions in the field of groundwater and ecology have been identified using statistical method in both CNKI and WOS databases. In the WOS database, the top ten research institutions based on the number of publications are the Chinese Academy of Sciences, the League of European Research Universities, the United States Department of the Interior, the United States Geological Survey, the University of California System, Helmholtz Association, Centre National De La Recherche Scientifique, United States Department of Agriculture, State University System of Florida and United States Department of Energy. Each of these institutions has published more than 190 articles. In the CNKI database, the top ten research institutions are China University of Geosciences, Beijing (CUGB), Jilin University, Chang’an University, Northwest A&F University, Hehai University, Lanzhou University, Xi'an University of Technology, Beijing Forestry University, The Xinjiang Institute of Ecology and Geography of the Chinese Academy of Sciences and Xinjiang University. Each of these institutions has published more than 300 articles (Table 3).

2.2.3 Major journal sources

The main medium for disseminating scientific achievements, i.e. journals, was identified after analyzing the related articles in both the CNKI and WOS databases. The distributions of journals in a research field can highlight its theoretical and practical value. The top five journals in the WOS database for groundwater and ecology are Science of the Total Environment, Journal of Hydrology, Agriculture Ecosystems Environment, Hydrological Processes and Water Resources Research. Each of these journals has published more than 200 articles. In the CNKI database, the top five journals in the field of groundwater and ecology are Ground Water, China Water Resources, Journal of Arid Land Resources and Environment, Hebei

Table 3 Top ten institutions in number of published articles in WOS and CNKI databases

WOS		CNKI	
Institutions	**Number of articles**	**Institutions**	**Number of articles**
Chinese Academy of Sciences	574	China University of Geosciences（Beijing）	581
League of European Research Universities Leru	469	Jilin University	549
United States Department of the Interior	363	Chang’an University	536
United States Geological Survey	341	Northwest A&F university	406
University of California System	311	Hohai University	353
Helmholtz Association	294	Lanzhou University	347
Centre National De La RechercheScientifiquecnrs	281	Xi’an University of Technology	343
United States Department of Agriculture USDA	254	Beijing Forestry University	334
State University system of Florida	235	Xinjiang Institute of Ecology and Geography Chinese Academy of Sciences	321
United States Department of Energy Doe	199	Xinjiang University	303

Water Resources and Heilongjiang Hydraulic Science and Technology. Each journal has published more than 130 articles.

2.3 Major hotspot topics

Research hotspots in an academic discipline often represent its frontier studies, which can objectively reflect the trends of the discipline. It can help researchers making plans for future research.

2.3.1 Keywords clustering analysis

Keywords can provide a high-level overview of the content and perspective of a topic, and can help to identify its focuses and directions. Therefore, the hotspots of research can be revealed through keyword clustering analysis of relevant references. To identify the research hotspots of groundwater and ecology studies over the past 20 years, the keywords of relevant articles and publications in both CNKI and WOS database from 2002 to 2022 were analyzed using CiteSpace software. The results are presented in Fig. 2 and Fig. 3.

The figures demonstrate that 13 clusters have been formed in the CNKI database: #0 Groundwater, #1 Ecological water conveyance, #2 Water Resources, #3 Water Ecology, #4 Countermeasures, #5 Ecological Environment, #6 Recycled Water, #7 Integrated Management, #8 Numerical Modelling, #9 Ecology, #10 Yellow River Basin,

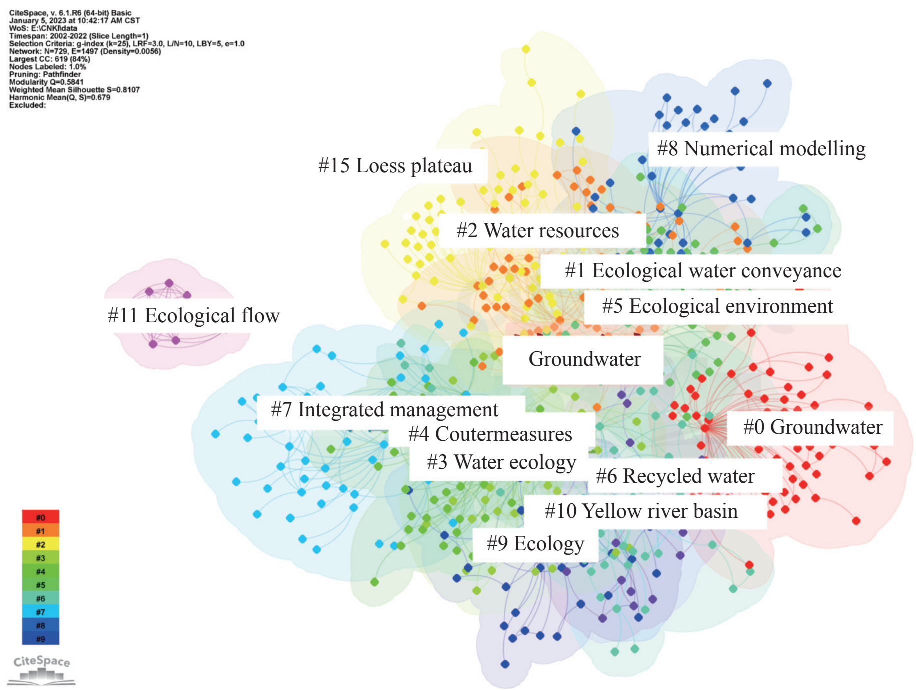

Fig. 2 Keyword clustering analysis in the study of groundwater and ecology in CNKI Database (2002–2022)

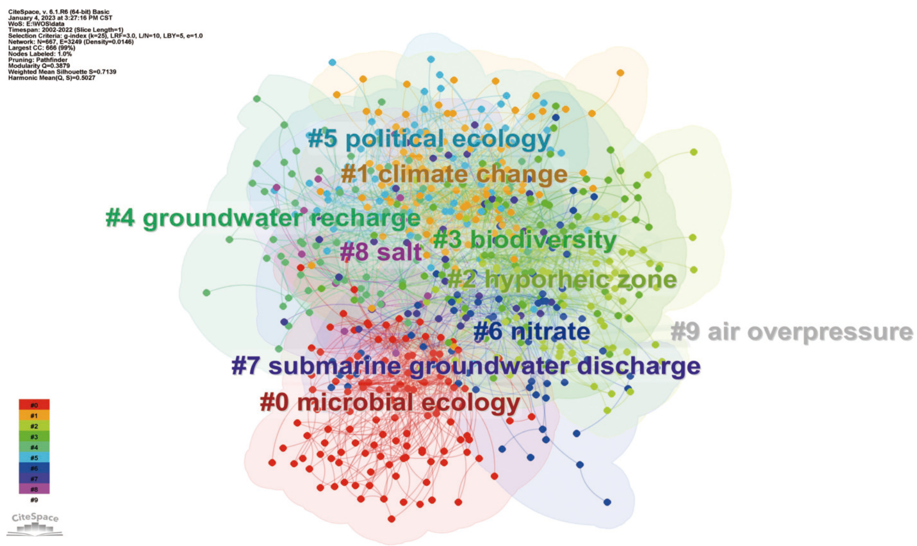

Fig. 3 Keyword clustering analysis in the study of groundwater and ecology in WOS Database (2002–2022)

#11 Ecological Flow and #15 Loess Plateau. These clusters are arranged in descending order of the number of nodes, with the smaller number indicating more keywords in the cluster. The category results of the 13 clusters are shown in Fig. 2, with Modularity (Q value) = 0.584 1 and Silhouette (S value) = 0.810 7. Meanwhile, 10 clusters are formed in the WOS database: #0 microbial ecology, #1 climate change, #2 hyporheic zone, #3 biodiversity, #4 groundwater recharge, #5 political ecology, #6 nitrate, #7 submarine groundwater discharge, #8 salt, #9 air overpressure. The category results of the 10 clusters are shown in Fig. 3, with Modularity (Q value) = 0.387 9 and Silhouette (S value) = 0.713 9. Generally, when the Modularity of a cluster is larger than 0.3 (Q value > 0.3), the cluster is structurally significant. When the Silhouette of a cluster is larger than 0.7 (S value > 0.7), the cluster is convincing (Chen et al. 2015). Therefore, it can be concluded that the clusters in this article are both structurally significant and convincing. The hotspots of groundwater and ecology research from 2002 to 2022 are mainly in these 23 topics. Foreign researchers focus on microbial ecology, climate change, groundwater-surface water interactions in hyporheic zones, biodiversity, political ecology, and submarine groundwater discharge, while researchers in China focus on water resources, water ecology, ecological water conveyance, ecological flow, protection and integrated governance of groundwater and ecology. Such differences suggest that domestic researchers concentrate more on the practical solutions and application of technologies, while the theoretical depth of domestic research is still not adequate, leaving a significant gap compared to the international level in research depth and scope.

2.3.2 High-frequency Keywords

The frequency of keywords also suggests research hotspots in a given discipline. Therefore, by sorting keywords based on frequency, researchers can improve their understanding of the research filed. The analysis of high-frequency keywords can help infer major research directions, research methods and hotspots. To achieve this, this paper utilized CiteSpace software to analyze related articles about groundwater and ecology in the CNKI and WOS databases from 2002 to 2022. The top 50 high-frequency keywords extracted from these articles are presented in Table 4.

The top 50 high-frequency keywords in CNKI and WOS databases in Table 4 demonstrate the main research hotspots in the field from 2002 to 2022. During this period, major research topics contain groundwater, ecosystems, surface water, recycled water, water environment, water ecology and the interactions in hyporheic zones. The main issues include groundwater level, water resource exploitation, integrated governance of water pollution, ecological restoration, ecological recharge of water, protection of water environment, biodiversity, groundwater quality, vegetation, soil, land use, sponge cities, and evolution and prediction of water-related issues. The key study areas are wetlands, mining areas, the Tarim River basin, the Yellow River basin and Hebei Province. The major influencing factors are climate change, human activities, water-rock interaction, hydrochemical action and microbial action. It blends many disciplines such as hydrogeology, water resources, hydro-geochemistry, ecology, microbiology and groundwater microbial ecology. The major res-

Table 4 High frequency keywords for groundwater and ecology in WOS and CNKI database（2002–2022）

CNKI				WOS			
NO	**Cited frequency**	**Year**	**Keywords**	**NO**	**Cited frequency**	**Year**	**Keywords**
1	1 005	2002	Groundwater	1	501	2002	Groundwater
2	330	2002	Water resources	2	363	2002	Water
3	286	2002	Ecological environment	3	358	2002	Ecology
4	112	2006	Numerical modelling	4	269	2002	Diversity
5	87	2003	Groundwater level	5	258	2002	Climate change
6	87	2017	Comprehensive treatment	6	194	2003	Dynamics
7	79	2003	Development and utilization	7	191	2002	River
8	79	2011	Ecological remediation	8	183	2002	Soil
9	71	2003	Ecologic water conveyance	9	177	2002	Pattern
10	68	2003	Countermeasure	10	171	2002	Management
11	64	2018	Ecological water compensation	11	170	2002	Biodiversity
12	57	2002	Ecological water requirement	12	162	2006	Impact
13	55	2002	Water environment	13	159	2002	Vegetation
14	50	2003	Tarim River	14	140	2002	Community
15	45	2003	Surface water	15	133	2003	Surface water
16	44	2009	Protection	16	133	2002	Ecosystem
17	44	2003	Evaluation index system	17	124	2004	Flow
18	43	2002	Soil	18	119	2002	Aquifer
19	42	2004	Influence	19	114	2002	Steam
20	41	2005	Evaluation	20	108	2002	Growth
21	39	2005	Reuse water	21	107	2002	Model
22	37	2016	Over-mining area	22	106	2002	Water quality
23	36	2005	Optimal configuration	23	101	2002	Sediment
24	34	2017	Sponge City	24	100	2002	Nitrogen
25	33	2005	Arid region	25	98	2002	Microbial community
26	33	2016	Water quality	26	86	2010	Stable isotope
27	33	2007	Ecosystem	27	85	2007	Land use
28	32	2012	Pollution	28	81	2002	Temperature
29	32	2020	Ecological flow	29	79	2002	Bacteria
30	31	2008	Measure	30	78	2002	System
31	31	2008	Vegetation	31	77	2009	Quality
32	30	2017	Hydrogeology	32	77	2003	Carbon
33	29	2002	Human activities	33	76	2007	Drinking water
34	29	2016	Water chemistry	34	74	2002	Hyporheic zone
35	28	2003	South-North water transfer project	35	71	2005	Forest
36	28	2013	Water ecology	36	70	2004	Transport
37	27	2002	Ecology	37	70	2007	Habitat
38	27	2012	Populus diversifolia	38	69	2003	Variability
39	26	2016	Environmental implication	39	68	2003	Nitrate
40	25	2007	Protection measures	40	68	2008	Heavy metal
41	25	2012	Coal mining with water conservation	41	67	2006	Basin
42	25	2009	Analysis	42	67	2002	Degradation
43	25	2014	Influence factors	43	67	2002	Spnov
44	25	2002	Climate change	44	64	2003	Organic matter
45	25	2011	Wetland	45	63	2009	Evolution
46	25	2004	Forecast	46	63	2002	Plant
47	25	2020	Yellow River	47	63	2002	Wetland
48	25	2016	Water sources	48	62	2008	Conservation
49	24	2016	Hebei province	49	59	2007	Microbial ecology
50	23	2015	Environmental protection	50	57	2009	Ecosystem service

earch methods are water chemistry, numerical modelling, isotopes and bioremediation techniques.

2.3.3 Characteristics of research hotspots

The research hotspots of groundwater and ecology research and their changes over time can be identified through the analysis of high-frequency keywords and keyword clustering, as described above. Based on such analysis, the main characteristics of the research hotspots both domestically and internationally, during the period of 2002–2022 are as follows:

(1) Increasing research topics with more details

Initially, the research topics in groundwater and ecology were broad, covering areas such as groundwater, water resources, ecological environment, water environment, soil, human activities, ecology and climate change. These topics have evolved to become more interdisciplinary, with studies focusing on areas such as groundwater and ecology, microbiology and environmental science. Similarly, research issues have become more specific, including groundwater levels, ecological water conveyances, evaluation index system, ecological restoration and ecological compensation. With the development of science and technology, as well as progress in the concept of ecological civilization, researchers have shifted their focus from utilizing water to protecting it from pollution and managing water resources. The ultimate goal is to strike a balance between groundwater and ecology to achieve sustainable development. Along with economic development, the impact of industrial and agricultural activities on groundwater resources and the environment has become more apparent. Consequently, keywords such as heavy metals, pollution, drinking water, nitrate, organic matter and groundwater quality frequently emerge in related articles. This indicates that researcher are paying extensive attention to the distribution, concentration and transferring process of these substances in groundwater.

Recent research has shown a shift from focusing on a single research object, such as individual water bodies, to investigating interaction among multiple water bodies, even to examining changes to the water cycle in the ecosystem. This transformation indicates that the current research is more multi-dimensional. Currently, human activities have a significant impact on groundwater properties, triggering a series of ecological and environmental effects. As a result, research in the field has also moved from just studying groundwater-ecosystem interaction to more interdisciplinary research that combines hydrogeology with ecology, microbiology biogeochemistry and other disciplines. With the emergence of new research technologies, methods and theories, current research has transitioned to multi-element driven approach and involves multi-temporal and spatial processes.

(2) The transformation of hot research areas in China shows a high policy orientation

Analysis of the keywords above reveals that the hot research areas in China include the Tarim River, the South-to-North Water Diversion Project, arid regions, wetlands, the Yellow River Basin, and the Chaobai River. The occurrence of these research fields is highly related to government policies.

For example, the Tarim River is a typical inland river basin in China. Since 2000, the ecological water conveyance implemented in the lower reaches of the Tarim River has increased the groundwater level, and gradually improved the water quality, land desertification control, and vegetation restoration, bringing great eco-environmental and socioeconomic benefits. The South-to-North Water Diversion Project is China' s major strategic infrastructure dealing with the water shortage problem in northern China, particularly in the Huang-Huai-Hai watershed. Since 2000, the planning of this project has been conducted orderly. In 2003, the construction of the emergency water supply project in the Beijing-Shijiazhuang section of the middle line of this project was started, which signaled the official commencement of the South-to-North Water Diversion Middle Line Phase I Project. In 2013, the Eastern Line Phase I Project started to operate formally. The water resources in the arid areas of northwest China are of great significance for China's western development strategy. These areas are short of water resources due to low precipitation and high evaporation. However, the protection of natural lake wetlands, natural vegetation, and oasis as well as the degree of soil salinization are highly reliant on the ecological groundwater reserve, making northwest China a typical ecologically fragile area. In March 2000, China's western development strategy was put into operation. Then in December 2006, the "Eleventh Five-Year Plan of China's Western Development" was passed to strive for the rapid and balanced economic development of western China, as well as to make breakthroughs in its infrastructural and eco-environmental construction. Therefore, the arid areas of northwest China have always been the hot research areas in groundwater and ecological studies. Wetland protection and restoration have been highly emphasized since the 18th Party Congress in 2012. The Party Central Committee with Comrade Xi Jinping at its core considers wetland protection and restoration as a vital element for ecological construction. With a series of decisions and deployments implemented, China's wetland protection and restoration have achieved historic achievements and transformation. The wetland is known as the "Kidney of the Earth" and the "Species Gene Pool". Together with forests and oceans, these are called the three ecosystems of the earth. Wetlands have numerous ecological functions, including water conservation, water purification, biodiversity maintenance, flood storage and drought prevention, climate regulation, as well as carbon storage and carbon sequestration. That's why wetlands are significant for maintaining ecological, food, and water resources security. Wetland restoration is urgent to fully play their ecological functions, to further improve the ecological environment and promote ecological civilization.

Researches in the past 3 years have emphasized the significance of the Yellow River Basin in developing China's economy and society, and in protecting China's ecological security. The Basin is crucial for China's poverty alleviation. Protecting the Yellow River is the key to achieving the great rejuvenation of the Chinese nation and the sustainable development of China. On September 18th, 2019, Comrade Xi hosted the Seminar on Ecological Protection and High-quality Development of the Yellow River Basin in Zhengzhou, where he made a keynote speech. In the speech, Xi proposed that the major national strategy is to protect the ecological environment and promote the high-quality development of the Yellow River Basin. In detail, this strategy focuses on enhancing the protection and governance of the Yellow River. By promoting the high-quality development of the Basin, the strategy includes supporting the poverty alleviation work in provinces and regions along the River, resolving people's concerns for flood control, water supply, and ecological safety, and ensuring the lasting stability of the Yellow River. In terms of the Chaobai River, as the only surface water source in Beijing, it is of great strategic significance. In 2021 and 2022, two ecological water supplements were completed respectively in the Chaobai River, which has greatly eased the situation of water shortage in the area. The use of water supplements put Beijing's strategic decision of "reservoir water underground" into implementation and realized the collaborative remediation of surface water and groundwater. The supplement has improved the ecological environment in the Chaobai River Basin. Therefore, this Basin is representative of the study of groundwater ecological compensation mechanism.

(3) Numerical simulation is the main research method, with other methods gradually introduced

From the changes in keywords, it can be inferred that numerical simulation has been the most commonly method to conduct groundwater and ecological studies. Then, several high-frequency keywords occurred, including nitrogen, phosphorus, organic carbon, microorganisms, and tracers, which means high emphasis on the analysis of chemical constituents, organic matter, and tracers in groundwater had also been noticed. Through quantitative analysis of chemical elements, isotopes, and organic matter contents, as well as the interactions between the different elements, the evolutionary process of groundwater quality and the chemical and biological process within this process can be explored. At present, the concept of the biogeochemical cycle has been further understood. The frequent occurrence of keywords like vegetation, climate, salinization, and irrigation, indicates there is a growing research hotspot on studying the influence of different water bodies' interactions on the responses of physical, chemical, and biological processes generated by human activities and climate change under the water cycle. In addition, studies on submarine groundwater discharge and coastal aquifers have emerged, and the research focus will be on the influence of the water bodies' interactions within the continental waters-marine ecological system on the biological and chemical responses caused by human activities and climate change.

2.4 Research frontiers and trends

2.4.1 Keywords burst analysis

Research frontiers are scientific problems or subjects that emerge as burst terms from a collection of references during a certain period. They represent the most advanced and promising hotspots in corresponding research fields. The strength and burst period can reflect the research frontiers and tendencies of a certain field. Therefore, analyzing the keyword frequency of relevant published articles in different periods can help summarize the change tendency of research focuses over time.

To identify the contribution of each keyword in certain periods, the Top 20 burst terms from 2002–2022 was obtained by using keywords burst analysis in Citespace software, based on the articles from the WOS and CNKI databases. The Top 20 keywords with the strongest citation bursts from both databases were obtained and presented in Fig. 4. The time of year refers to the first time that the keyword occurs, strength refers to the strength of the burst term, the time of begin indicates the starting year of the burst, and the time of end represents the termination date of the burst term (Fig. 4). The burst terms that occurred in WOS and CNKI databases between 2002 and 2022 are listed and discussed below. These terms reflect the shift of research hotspots in the groundwater and ecological studies in 2002–2022 and represent the current and future research trends in these fields.

① In the CNKI database, the research frontier of groundwater and ecological studies was the ecological environment and ecological water requirement in 2002. In 2003, the research areas shifted to studies on the Tarim River and the lower reaches of Heihe River, with the frontier being the changes in natural vegetation and remote sensing as the main research method. This trend continued until 2010. From 2004 to 2010, the research frontiers were ecological effect and reasonable

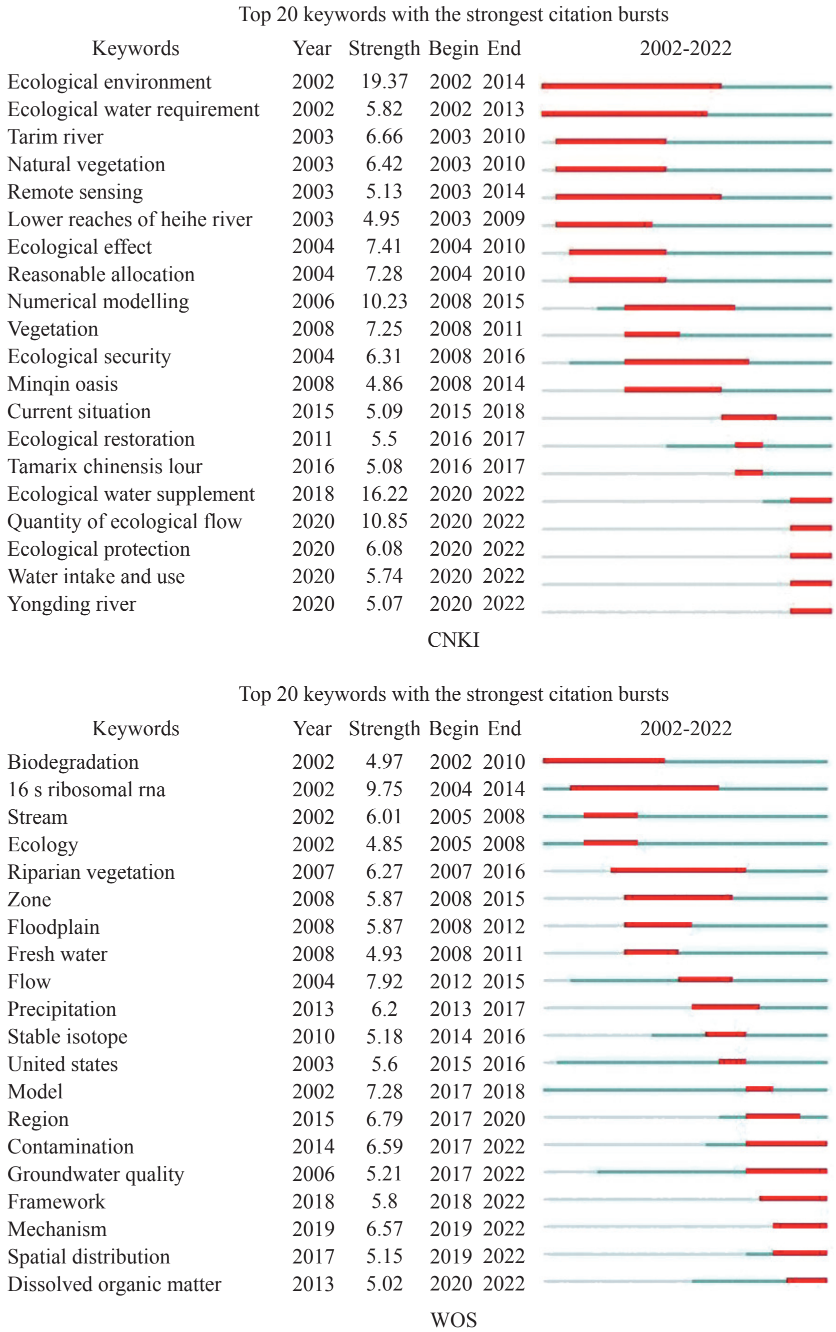

Fig. 4 Burst Terms based on CNKI and WOS Databases (2002–2022)

allocation, which lasted for six years. From 2008 to 2014, the research focuses shifted to ecological security and vegetation, which lasted for eight years and three years, respectively. The main research method during this time was numerical modelling, and the major area was the Minqin Oasis, which lasted for 6 years. Between 2015 and 2018, the frontiers shifted to the current situation and ecological restoration, with Tamarix chinesis Lour being the major research object. Since 2020, the research focus has shifted to ecological water supplement, quantity of ecological flow, ecological protection, and water intake and use, with the major research area being the Yongding River. These subjects represent the newest research frontier and will likely remain research hotspots in the next few years.

② In the WOS database, the research frontier of groundwater and ecological studies in 2002 was biodegradation. Then in 2004, the research frontier became 16S ribosomal RNA, the effect of which lasted for 10 years. Between 2005 and 2008, the research frontier shifted to stream and ecology. In this period, riparian vegetation was the research focus of 2007, and its effect lasted for 9 years. Later in 2008, the research focuses were the zone, floodplain, and fresh water, with the effect of the former (Zone) lasting for 7 years, while the effect of the latter two lasted for 3–4 years. From 2012 to 2015, the research frontiers were flow, precipitation, stable isotope, and united states, respectively. Research frontiers after 2017 include model, region, contamination, groundwater quality, framework, mechanism, spatial distribution, and dissolved organic matter, among which contamination, groundwater quality, framework, mechanism, spatial distribution, and dissolved organic matter have remained major focuses till now. These subjects remain to be the newest frontiers relatively and will likely continue to be the research hotspots in the coming years.

2.4.2 Timeline visualization of keywords co-occurrence clustering analysis

The keyword-timeline visualization analysis presented in this study provides a graphical representation of the evolution of research hotspots in groundwater and ecological studies. Each keyword is placed in the corresponding position based on the cluster and publication date it belongs to, with keywords in the same cluster placed in the same horizontal line chronologically. Keywords in each cluster are strung in the same timeline to show the historical achievements of that cluster, and the high-frequency keywords can reflect the subject's research hotspots directly. By analyzing the sequence of keywords in the coordinate axis, changes and tendencies in research hotspots of the field can be accurately explained. The research time span for this study was from 2002 to 2022, with a time slice of one year, and the keyword cluster analysis of groundwater and ecological was conducted using Citespace software (Fig. 5 and Fig. 6).

From 2002 to 2022, the keyword co-occurrence

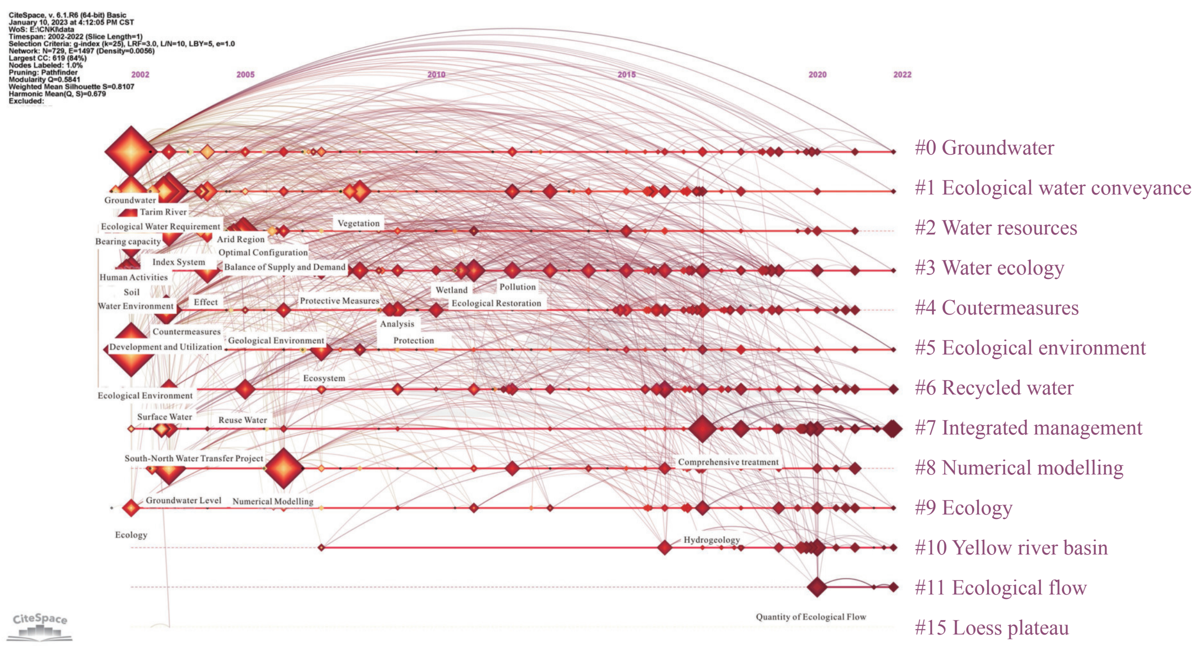

Fig. 5 Keywords-Timeline visualization analysis based on groundwater and ecological studies in CNKI Database (2002–2022)

Fig. 6 Keywords-Timeline visualization analysis based on groundwater and ecological studies in WOS Database (2002–2022)

timeline from relevant literature about groundwater and ecological studies in CNKI and WOS databases drew 13 and 10 cluster tags (Fig. 5 and Fig. 6). These clusters represent the changes in research hotspots in groundwater and ecological studies and provide insight into the research trends and focuses. In these clusters, ecological water supplement, climate change, and hyporheic zone were the main focuses of the research, while studies on water ecology and biodiversity were the most lasting. Groundwater, water resources, measures, ecosystems, water recharge, ecology, groundwater supplement, political ecology, nitrate, and submarine groundwater discharge were important research contents. Numerical simulation was the most used method. In recent years, comprehensive management, the Yellow River Basin, ecological flow, the Loess Plateau, and salt have been contents attracting attention. In summary, the changes in research hotspots in groundwater and ecological studies at home and abroad can be divided into three stages:

(1) Before 2007, the international research hotspots were mainly focused on the ecological environment under natural conditions, including natural landscapes, rivers and lakes, soils, and phreatic water. The research mainly focused on the microbiological field, such as biodegradation and metabolism. Among these studies, the 16S ribosomal RNA drew the most attention from researchers. On the other hand, domestic research focused on the analysis of the ecological environment under natural conditions, with major research areas including the Oasis, the Tarim River, and the lower Heihe River. Domestic studies mainly took the natural vegetation as the research objects and investigated the ecological water requirement, water use, and rational and optimal allocation of resources under natural conditions.

(2) From 2008 and 2015, the international research hotspots shifted to the recharge, discharge, and exchange of water resources, as well as the studies on species richness in ecosystems and on CO_2. The researches were mainly conducted in the river flat, riparian zone, fresh water, groundwater, and natural landscapes, and the isotopic method was also adopted in this field. Meanwhile, in domestic research, ecological security became the focus, and numerical simulation became a popular research method. In China, research was mainly conducted in Minqin Oasis, Sanjiang Plain, and the middle reaches of the Heihe River. The research contents included the ecological environment, current situation, ecological water requirement, ecological security, and predictions. Furthermore, domestic researchers paid attention to biomass studies gradually.

(3) From 2016 and 2021, international studies mainly focused on the management of ecological problems, the formulation of laws and regulations, and the tendency predictions. The research areas included drinking water, groundwater, coral reef, and fauna. The main research topics were contamination and the fragility of ecosystems, with a focus on heavy metal pollution (iron in particular) and organic carbon. Meanwhile, domestic research

hotspots in China focused on ecological evaluation, restoration, and management. The arid areas and Oasis remained important research regions, but the ecological problems of the open-pit mining areas also became a focus. Additionally, the ecological water supplement of China's key areas, including the Yellow River Basin and the Yongding River Basin, received increases attention. Researchers focused on ecological problems after the development and utilization of underwater resources, methods to protect those resources, and the sustainable development of ecosystems. Heavy metal pollution also drew the attention of domestic scholars during this time period.

It can be concluded that groundwater and ecological studies have gone through significant evolution both domestically and internationally, transitioning from natural conditions to human intervention, from natural balance to artificial optimization, and from terrestrial ecosystems to marine ecosystems. Over the past two decades, concepts and technologies of multiple disciplines related to hydrology, geology, and ecology have enriched and improved groundwater and ecological studies. The occurrence of new technologies and methods has provided great opportunities for further development in this field. The studies have transitioned from studies on the evolution of groundwater biotic areas to interdisciplinary studies on hydrogeology, ecology, and microbiology. As the research subjects become more detailed, and the directions are further expanded, groundwater and ecological studies are expected to enter a new era of rapid development.

3 Conclusions

The studies of groundwater and ecological is vital for protecting the groundwater and ecological environment, promoting regional water security and ecological security, and constructing ecological civilization. Based on bibliometric methods, this paper analyzed the research teams and hotspots in this field by using Citespace software to collate relevant articles includes in the CNKI and WOS databases. The conclusions are as follows:

(1) Groundwater and ecological studies are primarily led by the United States, China, and Germany, with research institutes such as Chinese Academy of Sciences, League of European Research Universities Leru, the United States Department of the Interior, China University of Geosciences (Beijing), Jilin University and Chang' an University taking a significant role. Studies in this field have presented a steady rise since 2000, with international studies starting earlier than domestic studies. Although domestic studies in China started in 2001, it can be discovered that after 2001, the annual volume of studies in China surpassed that of databases abroad. This suggests that Chinese scholars have been paying significant attention to this field in recent years.

(2) Over the past two decades, research in groundwater and ecological studies, both domestically and internationally, has shown a focus on multi-factor coupling drive, multiple spatiotemporal interactions, and multi-discipline integration. International studies mainly focus on microbial ecology, climate change, groundwater-surface water interactions in hyporheic zones, biodiversity, political ecology, and submarine groundwater discharge, while domestic studies focus on water resources, water ecology, ecological water conveyance, ecological flow, protection methods and comprehensive management of underwater and ecology. International studies have placed more emphasis on the studies of mechanisms, the application of new methods, the prediction of tendencies, and the formulation of laws and regulations, while domestic studies have focused more on practical solutions and applications. However, research in China lacks the exploration of mechanisms, and domestic studies on submarine groundwater discharge and reliance on groundwater ecosystems are lagging behind. Some research topics lack depth and breadth compared to international studies, and the use of new methods should also be enhanced.

(3) In the past two decades, groundwater and ecological studies have gone through an evolutionary process, from natural conditions to human intervention, from natural balance to artificial optimization, and from terrestrial ecosystems to marine ecosystems. This evolution can be summarized and divided into three stages: Before 2007, studies both domestically and internationally focused on the eco-environmental situation under natural conditions; from 2008 to 2015, international studies primarily focused on the recharge, discharge, and exchange of water resources, while domestic studies focused on ecological security. From 2016 to 2021, international studies emphasized the management of ecological problems, the formulation of laws and regulations, and the tendency predictions, while domestic studies emphasized ecological evaluation, restoration, and management. Furthermore, the analysis of burst terms reveal that ecological water supplement, ecological flow, ecological protection, water intake and use, submarine groundwater discharge, contamination, groundwater qua-

lity, framework, mechanism, spatial distribution, and dissolved organic matter are the latest research frontiers currently, and these subjects will likely remain research hotspots for the coming years.

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