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Research Progress of Groundwater and Surface Water Interaction in Riparian Zone Based on Bibliometrics

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ABSTRACT

The interaction between groundwater and surface water was a key link in the study of hydrological and ecological processes in riparian zones. Based on the literature of the SCI-E database of the core collection of Web of Science as the data source, the CiteSpace bibliometric tool was used to visualize the research literature on the interaction between groundwater and surface water in the riparian zone from the aspects of annual publication volume, research strength, subject distribution, and research hotspot frontier. The results showed that the number of research papers on the interaction between groundwater and surface water in the riparian zone was on the rise. The United States had the strongest research strength, while China needed to strengthen exchanges and cooperation with scientific research institutions in other countries. Research institutions such as the Chinese Academy of Sciences, Colorado State University, and the US Geological Survey had published a large number of papers. Soulsby C, Groffman P M, and Hill A R were the core authors. Journals such as Journal of Hydrology, Hydrological Processes, and Water Resources Research were the main carriers. Keyword co-occurrence analysis showed that the multi-level environmental interface dynamic process of surface water and groundwater, the coupling of hydrological-biogeochemical processes in riparian zones, and the eco-environmental effects of the interaction between groundwater and surface water were the core contents of the research on the interaction between groundwater and surface water in riparian zones. From keyword clustering and burst analysis, it could be seen that diversified comprehensive research methods, the source-sink model of nutrient elements in the riparian zone, the formation and evolution mechanism of groundwater under changing environments, and its geological-ecological effects were the frontier hotspots in the field of interaction between groundwater and surface water in the riparian zone.

KEYWORDS

Riparian zone; Groundwater and surface water; CiteSpace; Bibliometrics; The Web of Science Core Database.

1. INTRODUCTION

Groundwater and surface water, as two major components of the hydrological cycle, exhibit close hydraulic connectivity and frequent mutual transformation in nature, serving as critical factors influencing regional water resource formation and structural characteristics[1]. Under the impacts of climate change and human activities, the exchange processes between groundwater and surface water have become increasingly frequent and dynamic. This influence has progressively extended to the entire hydrological cycle, ultimately threatening ecosystem sustainability[2-4]. Due to limitations in technical methods and data availability, the study of groundwater-surface water interactions remains a key challenge in hydrogeology and hydrology that requires further exploration[5].

Riparian zones, as critical transitional ecosystems between riverine and terrestrial systems, exhibit pronounced edge effects and possess unique structures, processes, and functions[6, 7]. As a special zone of multi-phase coexistence, the water-rock interaction, microbial activity and frequent migration and transformation of materials and nutrients in riparian zone involved the coupling of physical-chemical-biological processes, and the interaction between groundwater and surface water was more complicated[8, 9]. With the expansion of the development scope and intensity of land resources around the river, the construction of water conservancy projects and the acceleration of urbanization, the structure of the riparian ecosystem changed, the ecological function degraded, and the ecological sustainability of the watershed landscape was reduced, which seriously threatened the health and stability of the regional ecosystem and the sustainable development of the social economy.[10, 11]. Therefore, the research on the interaction between groundwater and surface water in riparian zones was of great significance to the protection and restoration practice of riparian zones and the rational development and utilization of water resources in river basins.

Bibliometrics was a literature analysis method based on mathematical statistics, which could objectively reflect the development process, research status and future trend of a certain subject field[12, 13]. At that time, this method had been applied to the research field of water cycle for many times[14-17]. This paper took the relevant literature on the interaction between groundwater and surface water in riparian zone included in the SCI-E database of Web of Science core collection from 1990 to October 2022 as the research object, and used the visual analysis software CiteSpace to carry out development combing and visual measurement analysis, aiming to intuitively show the research process and development context in this field, and reveal the research hotspots and future development trends, so as to provide theoretical reference for the future research on the interaction between groundwater and surface water in riparian zone.

2. DATA SOURCES AND RESEARCH METHODS

2.1. Data source

The data analyzed in this paper were from the Science Citation Index Expanded (SCI-E) database of the Web of Science core collection. The Web of Science database was a citation index database launched by the U.S. Institute of Science and Technology, which contained the world's most influential academic achievements[18]. This article used the basic retrieval method, the specific search conditions were: theme: (riparian*) AND theme: (groundwater or 'ground water') AND theme: (river* or surface*) AND theme: (interact*) AND literature type: (Article) AND language: (English), the time span was 1990-2022, and the data retrieval time was as of December 31, 2022. The search results were screened one by one, and the irrelevant and repetitive literatures were eliminated. Finally, 391 literatures related to the interaction between groundwater and surface water in riparian zone were obtained. The screened literature was downloaded and saved as a pure text file in the format of 'full record and cited references', which was used as a data source for analysis.

2.2. Research methods

This paper used the CiteSpace software developed by Professor Chaomei Chen of Drexel University in the United States based on the Java language for analysis[19]. Through data mining and map drawing, CiteSpace software realized the visualization of analysis results, intuitively displayed the knowledge structure of specific subject areas, and obtained the research status, research hotspots and future development trends in this field[20]. In this paper, the knowledge map of the field was drawn by visual analysis of the annual publication volume, research strength, subject classification, journal source and keywords in the research field of the interaction between groundwater and surface water in riparian zone, so as to explore the development process, research status, research hotspots and future development trend of the research field of the interaction between groundwater and surface water in riparian zone.

3. RESULT AND DISCUSSION

3.1. Trends in annual publication volume

The number of published papers could represent the degree of attention of researchers to a certain research field, and the age distribution of articles could reflect the research process and development speed of the field to a certain extent[21]. From 1990 to 2022, the number of published papers on the interaction between groundwater and surface water in riparian zones showed an overall upward trend (Fig. 1). The research on the interaction between groundwater and surface water in riparian zone was roughly divided into two stages: the first stage (1990-1999) was the initial stage of the research on the interaction between groundwater and surface water in riparian zone. At this stage, the number of literatures published was small and the growth trend was not obvious. The average annual number of publications was less than 2 articles, and the cumulative number of publications was 19, accounting for 4.92% of the total number of publications. The research at this stage mainly focused on the water quality and water exchange between groundwater and surface water in the riparian zone[22]、nutrient migration[23]and denitrification process[24]. The transformation relationship between groundwater and surface water was mainly qualitative analysis[25]. The second stage (2000-2022) was the stable development stage of the study on the interaction between groundwater and surface water in riparian zone. More scholars began to pay attention to this field. The annual number of publications was about 16, and the cumulative number of publications was 372, accounting for 95.14% of the total number of publications. During this period, the research field made great progress in terms of research scale, scope and methods [1, 26-28], and the research content also expanded to focus on regional ecological environment problems and restoration methods caused by human activities and climate change[29-32]. In the past 30 years, with the attention and research of more and more scholars, the number of publications in the field of groundwater-surface water interaction in riparian zones showed a significant increase. However, compared with other fields, the number of publications in this field was relatively low, indicating that there was still much room for development in this field in the future. With the rapid development of social economy and science and technology, the research on the interaction between groundwater and surface water in riparian zone received more attention.

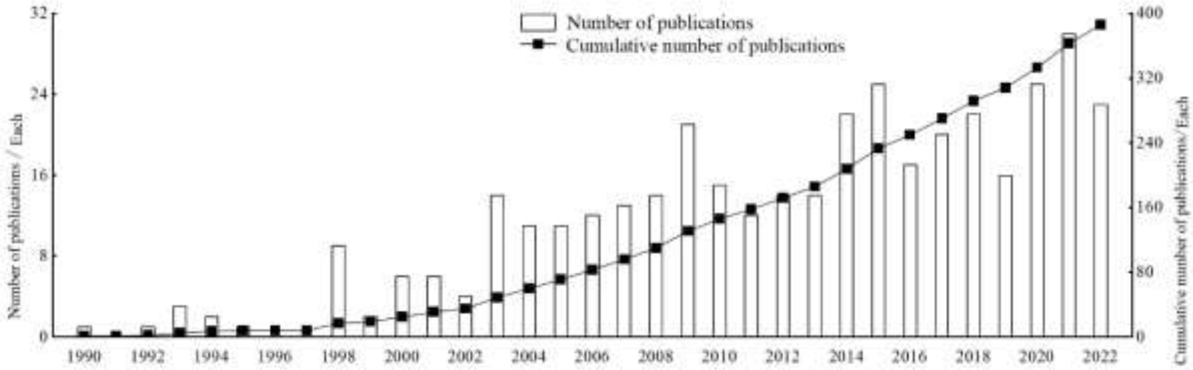

Figure 1. Trend of annual publication volume from 1990 to 2022(The data for 2022 is as of October 31,2022.)

3.2. Research distribution

3.2.1. Country/region distribution

The number of papers published by a country/region could reflect the activity and influence of research in a certain field to a certain extent[33]. According to the analysis of the search results of the

Web of Science core database, 386 articles on the interaction between groundwater and surface water in riparian zones from 1990 to 2022 were from 42 countries/regions around the world, of which 11 countries/regions published only one article. The total number of published articles in the top 10 countries since 1990 was shown in Table 1, and the cooperation network between countries was shown in Figure 2. The circular nodes in Figure 2 represented different countries. The larger the node was, the more the number of documents was issued. The connection between nodes represented the cooperative relationship between countries. The purple outer circle represented the betweenness centrality. The betweenness centrality was an indicator used to measure the importance of nodes in the network map. The higher the betweenness centrality, the thicker the purple outer circle was, if the betweenness centrality was greater than 0.1, the node was the key node in the network[34]. From Table 1 and Figure 2, we could see that the United States ranked first in the number of publications, with a total of 196 articles, accounting for 50.78% of the total number of publications, which was 4.08 times and 5.44 times that of China (second) and Germany (third) respectively. The intermediary centrality of the United States, Germany, the United Kingdom, and France was more than 0.1, which was 0.51, 0.28, 0.18, and 0.17, respectively, indicating that the four countries occupied an important position in the national cooperation network. The number of published papers and betweenness centrality in the United States were the highest, indicating that the United States had invested more scientific research in the field of interaction between groundwater and surface water in riparian zones, and had frequent exchanges with other countries and played an important role. China's research on the interaction between groundwater and surface water in riparian zones started late (the first year was 2012), and the betweenness centrality was low (0.04), indicating that China's research in this field was not yet at the core position, and it was necessary to strengthen exchanges and cooperation with scientific research institutions in other countries. The number of papers published by China in the field of groundwater-surface water interaction in riparian zone ranked second, especially in the past five years, the proportion of papers published was as high as 68.75%, showing a rapid increase trend, reflecting that China had received more attention and attention in this field in recent years, and had achieved remarkable scientific research results. It was expected that China would still develop at a faster rate in this field in the future.

Table 1. The top 10 countries in terms of the number of publications

	Country	Number of publications / Each	The proportion of papers published in the past 5 years / %	Betweenness centrality	Start year
1	USA	196	29.08	0.51	1992
2	China	48	68.75	0.04	2012
3	Germany	36	38.89	0.28	1998
4	England	31	22.58	0.18	1998
5	Australia	30	20.00	0.04	2005
6	Canada	30	16.67	0.00	1998
7	Switzerland	24	20.83	0.03	1998
8	France	21	9.52	0.17	1998
9	Scotland	12	33.33	0.10	2010
10	Netherlands	11	18.18	0.00	2003

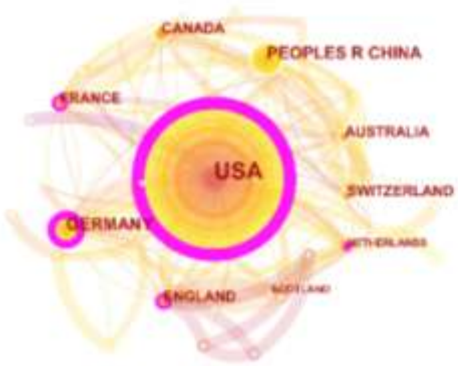

Figure 2. Top 10 countries' cooperation network map

3.2.2. Distribution of author's affiliations

The node type in CiteSpace was selected as 'institution', and the visualization analysis of the knowledge map of the publishing institutions was carried out to obtain the collaborative relationship network of various institutions in the research field of groundwater-surface water interaction in riparian zone (Figure 3). The network had a total of 555 nodes, indicating that 555 institutions had published academic achievements in this field. The low density of the network (0.0075) indicated that there was less cooperation among institutions in the research field of groundwater-surface water interaction in riparian zone. Table 2 was the top 10 research institutions in the field of interaction between groundwater and surface water in the global riparian zone from 1990 to 2022. Among the 10 institutions, the top 3 institutions with the highest number of publications were the Chinese Academy of Sciences, Colorado State University, and the US Geological Survey. The betweenness centrality of Colorado State University and the US Geological Survey was also relatively high, which was 0.20 and 0.15 respectively, and five of the top 10 institutions were from US government agencies and universities, indicating that US research institutions played an important role in the research field of groundwater and surface water interaction in riparian zones. The Chinese Academy of Sciences was a research institution with a high level of scientific research in China. It undertook a lot of research work and made outstanding contributions to the development of the research field of the interaction between groundwater and surface water in the riparian zone of China. In addition, the proportion of papers published by the Chinese Academy of Sciences in the past five years was as high as 60.00%, showing a rapid growth trend, and the betweenness centrality of the Chinese Academy of Sciences was 0.09, indicating that China's research institutions developed rapidly in the field of interaction between groundwater and surface water in riparian zones in recent years, and cooperated with other research institutions frequently.

Table 2. Top 10 research institutions in terms of number of published papers

	Institution	Number of publications / Each	The proportion of papers published in the past 5 years / %	Betweenness centrality
1	Chinese Academy of Sciences	15	60.00	0.09
2	Colorado State University	14	28.57	0.20
3	US Geological Survey	13	30.77	0.15
4	University of Arizona	12	16.67	0.07
5	University of Aberdeen	12	33.33	0.05
6	CSIRO Land and Water	10	10.00	0.08
7	Flinders University South Australia	10	30.00	0.09

Continued from table 2. Top 10 research institutions in terms of number of published papers

	Institution	Number of publications / Each	The proportion of papers published in the past 5 years / %	Betweenness centrality
8	University of Montana	10	10.00	0.09
9	US Forest Service	10	20.00	0.24
10	British Geological Survey	8	25.00	0.02

Figure 3. Top 10 research institutions cooperation network map

3.2.3. Distribution of authors

Through the analysis of the authors of the paper, we could understand the main research scholars in this field[35]. At that time, 1345 scholars around the world had published articles in the field of groundwater-surface water interaction in riparian zones. The top 10 authors in the number of publications were statistically analyzed, and the results were shown in table 3. According to Table 3, the most published scholar was Soulsby C from Humboldt University of Berlin. A total of 12 articles in this field were published, accounting for 3.11% of the total number of papers published, indicating that the research strength of Soulsby C's team in the field of groundwater and surface water interaction in riparian zone was strong, and the scientific research results were remarkable. Globally, 1345 scholars have published papers in the field of groundwater-surface water interactions in riparian zones. A statistical analysis was conducted on the top 10 most prolific authors, with the results presented in Table 3. According to the table, the leading contributor is Soulsby C from Humboldt University of Berlin, having published 12 papers in this field, accounting for 3.11% of the total publications. This demonstrates the strong research capabilities and outstanding scientific output of Soulsby C's team in this domain. Among other leading scholars, Wang P from the Chinese Academy of Sciences has published 80.00% of their total papers in the past five years, demonstrating recent high research activity. Similarly, Sawyer AH (The Ohio State University), Tetzlaff D (University of Aberdeen, UK), and Wang WK (Changan University) have also shown strong recent engagement, with 50.00%, 44.44%, and 40.00% of their respective total publications appearing in the last five years. This suggests that these four scholars have been particularly active in recent research on this topic. The author collaboration network map (Figure 4) reveals that the cooperative relationships among researchers in this field (based on the Web of Science Core Collection) exhibit small clustered groups but an overall dispersed pattern. This indicates that most collaborations are confined within individual research teams, with relatively independent and limited interactions between different groups. To foster further advancements, enhancing interdisciplinary and inter-team collaboration should be prioritized in future research efforts.

Table 3. The top 10 research authors in the number of published papers

	Author	Number of publications / Each	Institution	The proportion of papers published in the past 5 years / %
1	Soulsby C	12	Humboldt University of Berlin	33.33
2	Groffman P M	9	Cary Inst Ecosyst Studies，NY USA	0.00
3	Hill A R	9	York University	0.00
4	Tetzlaff D	9	University of Aberdeen	44.44
5	Gold A J	6	University of Rhode	0.00
6	Malcolm I A	6	Marine Scotland Sciences	0.00
7	Sauvage S	6	University of Toulouse	16.67
8	Sawyer A H	6	Ohio State University	50.00
9	Wang P	5	Chinese Academy of Sciences	80.00
10	Wang WK	5	Changan University	40.00

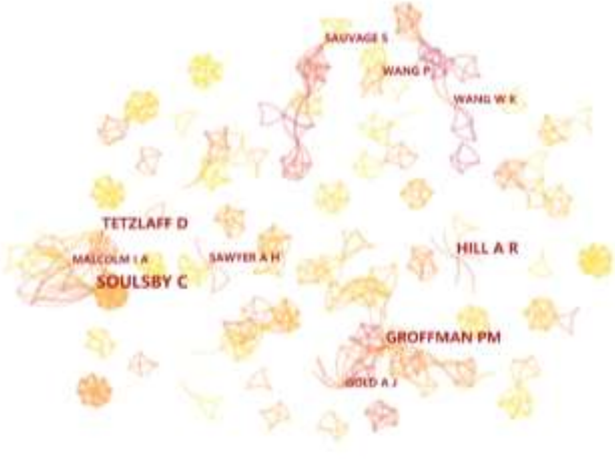

Figure 4. Top 10 authors' cooperation network map

3.2.4. Distribution of literature journals

Statistical analysis of journals publishing in a specific research field helps identify authoritative publications, enabling researchers to selectively review literature and target submissions for their work[36]. An analysis of literature on groundwater-surface water interactions in riparian zones from the Web of Science Core Collection (1990–2022) revealed that 386 articles were published across 112 journals. Table 4 lists the top 10 journals by publication volume. Journal of Hydrology ranked first, publishing 49 articles (12.69% of total publications), with an impact factor of 6.708. Hydrological Processes and Water Resources Research followed, publishing 38 and 36 articles, with impact factors of 3.784 and 6.159, respectively. The top three journals accounted for 31.87% of total publications, indicating a high concentration of research output in these outlets. The top 10 journals had relatively high impact factors, averaging 5.331. Among them, Science of the Total Environment (10.754), despite ranking 10th in publication volume, had the highest impact factor. According to the 2021 Journal Citation Reports, six journals (Journal of Hydrology, Water Resources Research, Hydrology and Earth System Sciences, Biogeochemistry, Freshwater Biology, and Science of the Total Environment) were classified as Q1. The remaining four had impact factors ranging from 2.695 to 4.379, falling under Q2 or Q3 categories. Notably, no Chinese journals ranked among the top 10, suggesting limited influence of domestic publications in this field and highlighting the need for further improvement in research quality.

Table 4. Top 10 journals in terms of number of published papers

	Source Publications	Number of publications / Each	JCR Quartile	Impact factors	Country
1	Journal of Hydrology	49	Q1	6.708	Netherlands
2	Hydrological Processes	38	Q2	3.784	England
3	Water Resources Research	36	Q1	6.159	USA
4	Hydrology and Earth System Sciences	17	Q1	6.617	Germany
5	Journal of the American Water Resources Association	15	Q3	2.695	USA
6	Ecological Engineering	11	Q2	4.379	Netherlands
7	Biogeochemistry	9	Q1	4.812	Netherlands
8	Freshwater Biology	9	Q1	3.538	England
9	Journal of Environmental Quality	9	Q2	3.866	USA
10	Science of the Total Environment	9	Q1	10.754	Netherlands

3.2.5. Comparison of research power

The number of publications can reflect the activity level and research focus of a research entity (country/region, institution, author, or journal) in a specific field, while the average citation count per paper can indicate the quality of the research and the influence of the entity in that field. By comprehensively analyzing both publication volume and average citations, we can assess the differences in research capabilities among various entities[37]. A comparative analysis of research strength was conducted from four perspectives: countries/regions, institutions, authors, and journals (Figure 5). At the country/region level, the United States had the highest number of publications, far exceeding the average, while its average citation count was moderate, indicating strong momentum in the field of groundwater-surface water interactions in riparian zones. Switzerland, Canada, and France, though not high in publication volume, had relatively high average citations, suggesting greater research influence. In contrast, Germany, England, Australia, Scotland, and the Netherlands had both lower publication counts and citation rates, indicating room for improvement in both quantity and quality. China ranked second in publication volume, but its average citation count was the lowest. Therefore, while maintaining a high output of publications, China should place greater emphasis on research quality to enhance the academic impact of its work.

From an institutional perspective, Colorado State University and the US Geological Survey ranked highly in both publication output and citations per paper, indicating their leading roles in the field of groundwater-surface water interactions in riparian zones. This further underscores the influence and research strength of the United States in this domain. Although University of Montana and the US Forest Service had relatively low publication counts, their citations per paper were significantly above average. In contrast, CSIRO Land and Water, Flinders University South Australia, and the British Geological Survey lagged in both publication volume and citation impact, suggesting room for improvement in research quality and output. Notably, the Chinese Academy of Sciences ranked first in publication quantity but had the lowest citations per paper, highlighting the need to enhance the academic impact of Chinese research in this field.

At the author level, Groffman P M and Hill A R demonstrated both high publication counts and strong citation performance, establishing them as leading figures in this research area. While Soulsby C had the highest number of publications, citations per paper were below average. Gold A J, despite a modest output (only 6 papers), achieved high citation rates, indicating influential research. Chinese scholars Wang P and Wang WK ranked 9th in publication count but had lower citations per paper, possibly because most of their work was published within the last five years.

Among journals, the top three in publication volume—Journal of Hydrology, Hydrological Processes, and Water Resources Research—had citations per paper below the average, suggesting that while they are key platforms for research in this field, there is room to improve publication quality. In contrast, Freshwater Biology, ranked 8th in publication count, had the highest citations per paper, reflecting its high academic standards.

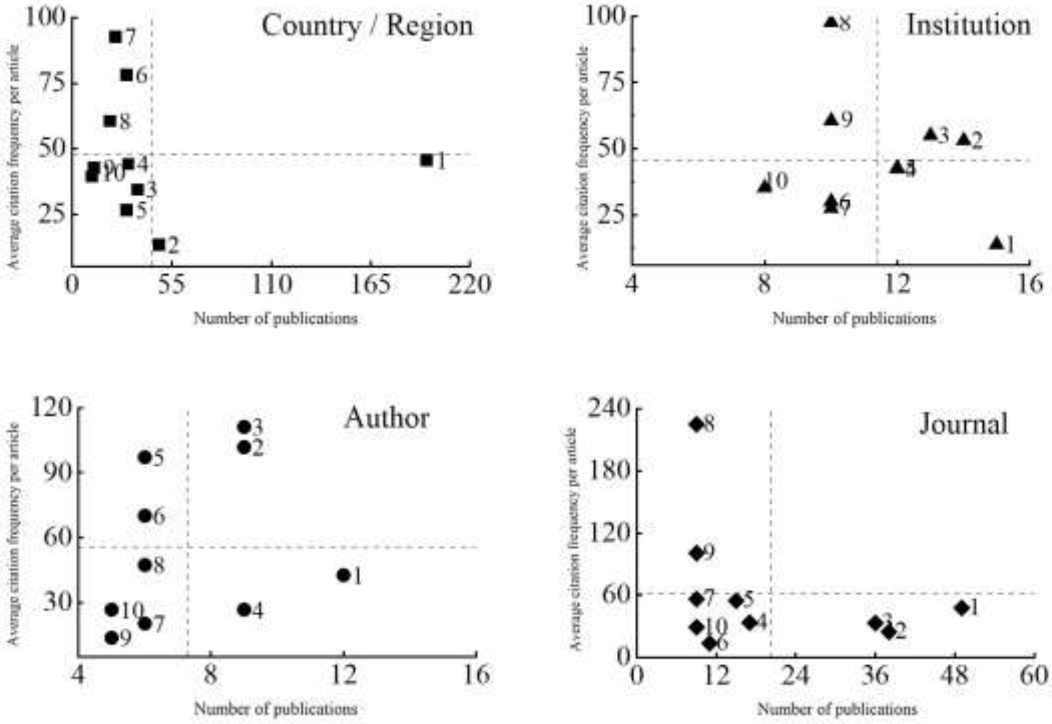

Figure 5. Comparison of research strength

The numbers in the four figures correspond to the serial numbers in Table 1-Table 4, and the intersection of the two dashed lines is the average of the number of publications and the average citation frequency.

3.3. Distribution of subject areas

Analyzing the disciplines involved in a research field helps clarify its main research directions. Figure 6 shows the top 10 disciplines by publication volume in the study of groundwater-surface water interactions in riparian zones. The primary disciplines include hydrology (56.99%), environmental science & ecology (50.26%), geology (35.23%), engineering (22.80%), and marine & freshwater biology (15.80%). Additionally, this research is connected to other fields such as agricultural science (4.92%), biodiversity conservation (2.59%), physical geography (2.59%), meteorology & atmospheric sciences (2.33%), and forestry (1.81%). The interaction between groundwater and surface water in riparian zones is a complex hydrological process influenced by multiple factors, including water resources, geological structures, and human activities. The interdisciplinary nature of this research reflects its breadth and comprehensiveness. While the diversity of involved disciplines presents opportunities for advancing the field, it also introduces additional challenges in integrating knowledge across different domains.

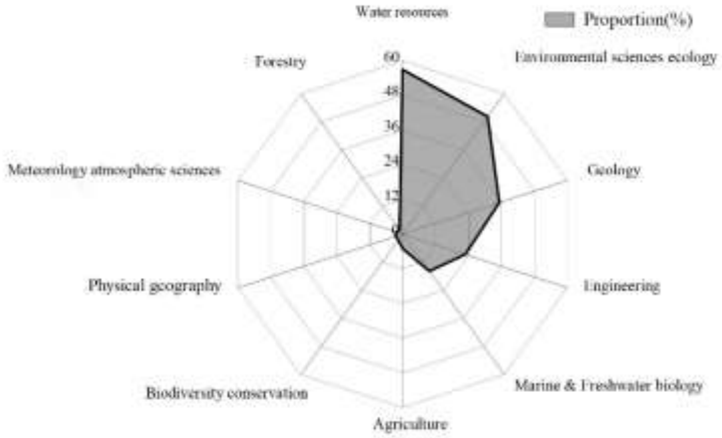

Figure 6. Distribution of disciplines of groundwater-surface water interaction in riparian zone

3.4. Keywords analysis

3.4.1. Research Content and Progress

Keywords are a highly condensed and refined summary of the core content and research themes of an article, representing its essence. High-frequency keywords extracted from relevant literature can reflect the research focus and direction in a particular field[38]. Co-occurrence analysis of keywords helps identify the current research trends in a given domain[39]. Using CiteSpace's keyword analysis function, we set the node type to "Keywor" and obtained a total of 257 keywords. Based on the top 40 high-frequency keywords (Table 5), we found that research on groundwater-surface water interactions (GSWI) in riparian zones mainly focuses on three aspects: Dynamical processes of groundwater-surface water exchange (e.g., surface water/river, groundwater, groundwater-surface water interaction, water, dynamics, exchange, transport, recharge, discharge, hydraulic conductivity, hyporheic, connectivity, heterogeneity, variability). Coupling of hydrological and biogeochemical processes in riparian zones (e.g., denitrification, pattern, nitrate, nitrogen, hydrology, model, organic carbon, stable isotope, tracer, water quality). Ecological effects of groundwater-surface water exchange (e.g., riparian zone, stream, vegetation, floodplain, wetland, ecosystem, management, impact, forest, land use, climate change, sediment, hyporheic zone, catchment). The dynamics of groundwater-surface water interactions have always been a central topic in riparian zone research. Since the French scientist Boussinesq first studied river-groundwater interactions in 1877, the recharge-discharge relationship between groundwater and surface water has attracted widespread attention. As their interactions have become more frequent and dynamic, the research scope has gradually expanded to the entire hydrological cycle. Interfacial dynamical processes will serve as a theoretical foundation for further developments in water cycle studies[1, 3, 40]. Interactions between groundwater and surface water alter hydrodynamic characteristics at hydrogeological and physical interfaces through hydraulic exchange, subsequently triggering hydrogeochemical evolution at chemical interfaces and biological responses at ecological interfaces[41]. Wang Wenke et al. revealed the complete dynamic process of river-groundwater interactions evolving from saturated linear connectivity to complete disconnection. They proposed that the hydraulic linkage between rivers and groundwater, as well as the dynamic processes at the riverbed interface, control the direction and intensity of river-groundwater exchange, significantly advancing the theoretical understanding of river-groundwater relationship evolution[42, 43]. Domestic and international scholars have conducted systematic research on the coupling between hydrological processes and biogeochemical processes in riparian zones. Riparian zones serve as critical hubs for groundwater-surface water interactions, where active physical, chemical, and biological processes occur. The dynamic exchange between groundwater and surface water drives the transport and transformation of materials, energy, and information within the riparian environmental system. Studies suggest that under seasonal hydrological regimes or the influence of upstream water conservancy projects, distinct physical and chemical gradients develop in riparian zones, leading to intense chemical and biogeochemical reactions during element migration. The water exchange process facilitates the mixing and transport of major ions, nutrients, persistent organic pollutants, and heavy metals in the hyporheic zone[44-47]. The ecological effects of groundwater-surface water exchange have long been a focal issue in riparian interaction research. Changes in the exchange relationship between rivers and groundwater not only alter the distribution pattern of water resources within a basin but also significantly modify soil saturation, groundwater salinity, and biogeochemical cycles, thereby impacting the entire ecosystem[48, 49]. Excessive river diversion, groundwater extraction, and hydraulic engineering constructions disrupt the natural exchange dynamics between rivers and groundwater, leading to environmental and ecological consequences such as baseflow depletion, shrinkage of water bodies, loss of wetlands and marshes, and soil salinization in downstream regions[50-52].

Table 5. Top 40 keywords and frequency of related literature

	Frequency	Keyword		Frequency	Keyword
1	123	surface water/river	21	25	soil
2	116	riparian zone	22	23	transport
3	111	groundwater	23	23	model
4	80	groundwater-surface water interaction	24	22	organic carbon
5	63	stream	25	20	management
6	57	dynamic	26	19	impact
7	55	vegetation	27	19	forest
8	51	denitrification	28	18	land use
9	50	flow	29	18	recharge
10	41	hypothetic zone	30	18	climate change
11	44	water	31	17	discharge
12	35	floodplain	32	17	sediment
13	31	exchange	33	11	stable isotope
14	29	pattern	34	10	heterogeneity
15	29	wetland	35	10	variabilit
16	29	nitrate	36	10	hydraulic conductivity
17	28	nitrogen	37	10	water quality
18	27	catchment	38	10	hypothetic
19	26	hydrology	39	10	tracer
20	26	ecosystem	40	9	connectivity

3.4.2. Research hot issues and frontiers

Keyword clustering reveals the frontier research hotspots in a specific field[16]. The keyword co-occurrence results are presented in a Timeline format, generating a keyword co-occurrence timeline graph (Figure 7). In the timeline graph, nodes within each cluster are arranged chronologically along their respective horizontal lines based on their first appearance. Each node represents a keyword, with node size indicating keyword frequency and line thickness reflecting co-occurrence relationships between keywords[19]. Analysis of Figure 7 shows that the clustering structure of research topics in groundwater-surface water interactions in riparian zones is highly significant, with good clustering effectiveness (Q=0.3317, S=0.8626). The keyword clustering timeline graph, based on Web of Science literature from 1990 to 2022, generated eight clusters: #0 hydrological/hydraulic modelling,

#1 floods, #2 salinity tolerance, #3 modflow, #4 stream, #5 environmental tracer, #6 stream chemistry, and #7 preferential flow. Among them, cluster 0, cluster 3 and cluster 5 mainly focus on the research methods of the interaction between groundwater and surface water in riparian zone. The interaction between groundwater and surface water in riparian zone develops from qualitative to quantitative research. Numerical coupling model and tracer techniques such as isotope and temperature are important research methods in the identification of the interaction between groundwater and surface water in riparian zone[27, 53-55]. Cluster 1, Cluster 4, and Cluster 7 mainly address the influencing factors of groundwater-surface water interactions. Human activities, climate change, and geomorphological conditions are key drivers of exchange dynamics. Factors such as flood pulse magnitude, riparian geomorphological changes, and upstream hydraulic engineering projects alter hydraulic connectivity between groundwater and surface water[56-59]. When media heterogeneity and anisotropy are pronounced, preferential flow pathways may form, leading to localized variations in hydrochemical characteristics[60]. During vertical flood recharge, rapid infiltration through deep soil matrices can replenish shallow groundwater via preferential flow[61]. Cluster 2 and Cluster 6 focus on the ecological impacts of groundwater-surface water interactions. Under seasonal hydrological regimes and anthropogenic influences, the exchange of water with varying chemical and nutrient concentrations participates in biogeochemical cycling in riparian zones. Particularly in arid regions, groundwater salinity and vadose zone salt content critically determine ecological heterogeneity[62, 63].

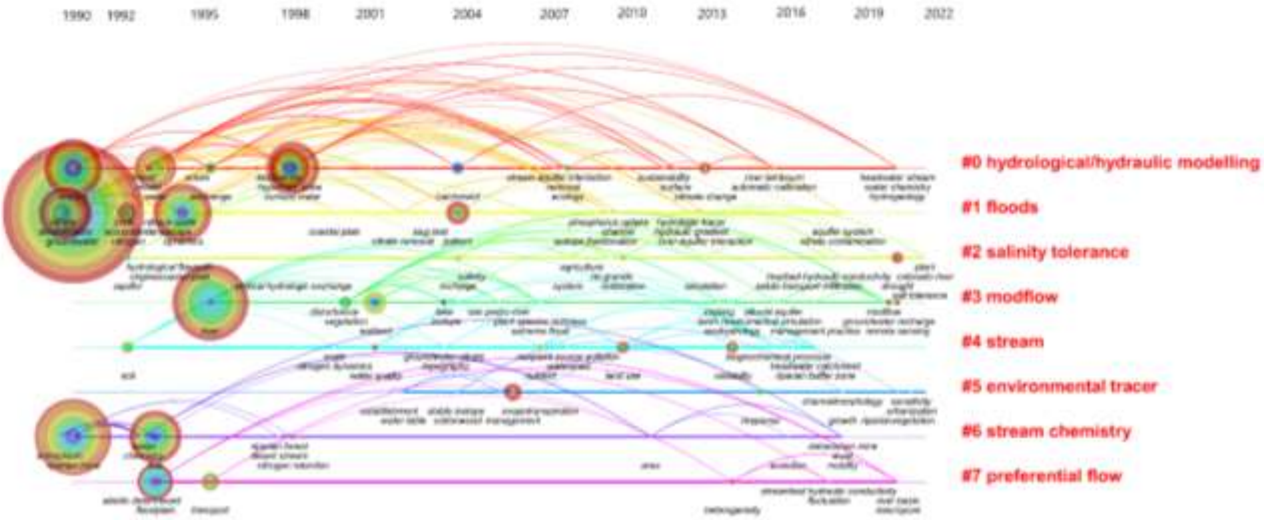

Figure 7. Keyword clustering timeline diagram

Burst terms refer to keywords or phrases that experience a sudden increase in frequency or growth rate over a short period. Their burst strength and duration can characterize the evolution of research frontier[64]. By conducting burst analysis on keywords, we can identify emerging trends and developmental dynamics in a specific research field. In this study, burst analysis was performed on keywords from literature related to groundwater-surface water interactions in riparian zones using CiteSpace. After merging terms with similar meanings, the top 20 keywords and noun phrases with the highest burst strength were selected (Table 6). In the figure, the blue line represents the time interval, while the red line indicates the burst period of a keyword, with its endpoints marking the start and end of the burst duration[65]. The analysis reveals that research in this field has gradually shifted from a singular focus to greater diversity. “Forest” emerged as the keyword with the highest burst strength (6.30, lasting 8 years) in the study of groundwater-surface water interactions in riparian zones. Related terms included “vegetation” (burst strength 3.48, duration 8 years). The spatiotemporal variations in river-groundwater exchange processes sustain the survival and evolution of surface vegetation. Upstream hydraulic engineering projects alter downstream hydrological regimes, leading to forest decline and desertification in riparian plant zones[66]. Particularly in arid regions (“drought,” burst strength 2.81, duration 3 years), hydrological changes in groundwater determine the structural composition and diversity of riparian plant communities. During flood seasons, riparian zones are dominated by hygrophytic herbs and mesic shrubs, whereas xerophytic herbs and moderately drought-tolerant shrubs prevail in dry periods[67]. Other high-burst terms included “floodplain” (4.46, 6 years), “catchment” (4.25, 4 years), “stream” (3.84, 10 years), “wetland” (3.11, 10 years), “hyporheic zone” (3.03, 2 years), “sediment” (2.96, 14 years), and “shallow groundwater” (2.75, 3 years). The research focus has evolved over time—from early studies on streambed sediments (burst period: 1994–2007), the hyporheic zone (1998–1999), and streams (2000–2009) to later investigations on catchments (2004–2007), wetlands (2004–2013), and floodplains (2006–2011). Recently, interactions between shallow groundwater (2016–2017) and surface water have become a key research focus. The coupled hydro-biogeochemical regulation mechanism in riparian zones has long been a key scientific focus for researchers worldwide. Riparian zones serve as critical interfaces for groundwater-surface water interactions, where the exchange between groundwater and surface water—driven by atmospheric precipitation and river runoff—plays a fundamental role in nutrient and carbon cycling, representing an internationally recognized frontier research topic[68]. The continuous exchange between surface water and groundwater through the hyporheic zone (hypothetic exchange, burst strength: 2.55, duration: 2 years) alters the transport (burst strength: 3.17, duration: 2 years) of dissolved and suspended substances, shaping the source-sink patterns of nutrients such as nitrogen (burst strength: 2.95, duration: 6 years), dissolved organic carbon (DOC, burst strength: 2.81, duration: 10 years), metal speciation, and organic pollutant degradation[44, 69]. Key terms such as denitrification (burst strength: 2.60, duration: 8 years), nitrate (burst strength: 3.81, duration: 10 years), and discharge (burst strength: 2.70, duration: 2 years) indicate water quality changes and their direct impacts. Furthermore, climate change (burst strength: 3.69, duration: 3 years) and intensified human activities have significantly altered regional hydrogeological conditions. The dynamics (burst strength: 2.69, duration: 2 years) at these interfaces govern material and energy fluxes, strengthening the coupling between groundwater, atmospheric precipitation, surface water, and ecosystems. Consequently, developing integrated groundwater-surface water models has become crucial for elucidating interaction mechanisms and quantitatively simulating their transformations[70, 71]. The three most recent burst keywords—climate change (2020–2022), drought (2020–2022), and hypothetic exchange (2018–2019)—highlight that the formation and evolution mechanisms of groundwater under changing environments, along with their geo-ecological effects, are currently at the forefront of riparian groundwater-surface water interaction research[62].

Table 6. Keywords emergent map of interaction between groundwater and surface water in riparian zone

	Keyword	Year	Intensity	Start year	End year	1990 – 2022
1	forest	1990	6.30	2000	2007	
2	floodplain	1990	4.46	2006	2011	
3	catchment	1990	4.25	2004	2007	
4	stream	1990	3.84	2000	2009	
5	climate change	1990	3.69	2020	2022	
6	vegetation	1990	3.48	2008	2015	
7	hydrology	1990	3.39	2008	2013	
8	nitrate	1990	3.18	2000	2009	
9	transport	1990	3.17	2014	2015	
10	wetland	1990	3.11	2004	2013	
11	hypothetic zone	1990	3.03	1998	1999	
12	sediment	1990	2.96	1994	2007	
13	nitrogen	1990	2.95	2008	2013	

Continued from table 6. Keywords emergent map of interaction between groundwater and surface water in riparian zone

	Keyword	Year	Intensity	Start year	End year	1990 – 2022
14	dissolved organic carbon	1990	2.81	1994	2003	
15	drought	1990	2.81	2020	2022	
16	shallow groundwater	1990	2.75	2016	2017	
17	discharge	1990	2.70	2008	2009	
18	dynamics	1990	2.69	2004	2005	
19	denitrification	1990	2.60	2000	2007	
20	hypothetic exchange	1990	2.55	2018	2019	

Note: All line segments in the table from 1990 to 2022 represent the data time period, in which the red bold line segment indicates the time period when the keywords are prominent, and the blue uncoarsed line segment indicates the time period when the keywords are not prominent.

4. CONCLUSION

Based on the SCI-E database from the Web of Science Core Collection (1990–October 2022), this study utilized CiteSpace visualization software to analyze the annual trends in publication volume, major research contributors, disciplinary distribution, and research hotspots and frontiers in the field of groundwater-surface water interactions (GSWI) in riparian zones. The main conclusions are as follows:

(1)Research on GSWI in riparian zones has shown an increasing trend. The United States leads in research strength globally, while China started relatively late and should enhance international collaboration. The top three institutions in terms of publication output are the Chinese Academy of

Sciences, Colorado State University, and the US Geological Survey. Research teams led by Prof. Soulsby C, Prof. Groffman P M, and Prof. Hill A R have significant academic influence and recognition in this field. Key journals include Journal of Hydrology, Hydrological Processes, and Water Resources Research. The interdisciplinary nature of this field spans hydrology, environmental science & ecology, geology, engineering, and marine & freshwater biology, reflecting a trend toward multidisciplinary integration.

(2)Analysis of high-frequency and high-burst keywords reveals that the core research themes focus on: Physicochemical-biological interfacial dynamics in riparian groundwater-surface water systems, coupling hydrological-biogeochemical processes using microbiological, hydrological, and biogeochemical approaches, and Eco-environmental effects of GSWI driven by hydrological, ecological, geomorphological, and biogeochemical processes.

(3)Based on the comprehensive research methods such as field measurement, new tracer isotope research and numerical simulation, based on the source-sink model of nutrient elements in riparian zone controlled by hydro-biogeochemical coupling, the formation and evolution mechanism of groundwater and its geological-ecological effects under changing environment and the development of targeted restoration measures are the frontier hotspots in the field of groundwater-surface water interaction in riparian zone.

In summary, as interdisciplinary integration deepens, research on GSWI in riparian zones has evolved from simplicity to complexity, with expanding prospects. Future efforts should strengthen multidisciplinary collaboration among hydrology, ecology, environmental science, geomorphology, oceanography, and climatology to advance a holistic understanding of riparian hydrological and biogeochemical processes, thereby enhancing ecosystem conservation and restoration.

CONFLICTS OF INTEREST

There are no conflicts of interest to declare.

REFERENCES

[1] LI Yunliang, YAO Jing, TAN Zhiqiang, et al. A review on the progress of surface water and groundwater conversion research in floodplain wetland systems[J]. Hydrology, 2019, 39(2): 14-21.

[2] XU Zongxue, LI Jingyu. Review and prospect of hydrological science research progress[J]. Advances in Water Science, 2010, 21(4): 450-459.

[3] DE GRAAF I E M, GLEESON T, RENS V B L P, et al. Environmental flow limits to global groundwater pumping[J]. Nature, 2019, 574(7776): 90-94.

[4] HE Xiaojia, WANG Guoqing, BAO Zhenxin. Research progress and prospect of climate and vegetation change impacts on hydrological cycle response[J]. Journal of Water Resources and Water Engineering, 2016, 27(2): 1-5.

[5] BLÖSCHL G, BIERKENS M F P, CUDENNEC C, et al. Twenty-three unsolved problems in hydrology (UPH)–a community perspective[J]. Hydrological Sciences Journal, 2019, 64(10): 1141-1158.

[6] HAN Lu, WANG Haizhen, YU Jun. Research progress and prospect of riparian zone ecology[J]. Ecology and Environmental Sciences, 2013, 22(5): 879-886.

[7] ZHAO Tongqian, XU Huashan, MENG Hongqi, et al. Formation mechanism and restoration theory of ecosystem services in riparian wetlands: A case study of the downstream floodplain area of Xiaolangdi Dam[M]. Beijing: Science Press, 2016.

[8] TENG Yanguo, ZUO Rui, WANG Jinsheng. The interface between surface water and groundwater and its ecological functions[J]. Earth and Environment, 2007, 35(1): 1-8.

[9] ZHU Aiping, YANG Zhigang, LIANG Zuobing, et al. Integrating hydrochemical and biological approaches to investigate the surface water and groundwater interactions in the hyporheic zone of the Liuxi River basin, southern China[J]. Journal of Hydrology, 2020, 583: 124622.

[10] SUNIL C, SOMASHEKAR R K, NAGARAJA B C. Impact of anthropogenic disturbances on riparian forest ecology and ecosystem services in Southern India[J]. International Journal of Biodiversity Science, Ecosystem Services & Management, 2011, 7(4): 273-282.

[11] MURGULET D, MURGULET V, SPALT N, et al. Impact of hydrological alterations on river-groundwater exchange and water quality in a semi-arid area: Nueces River, Texas[J]. Science of the Total Environment, 2016, 572: 595-607.

[12] NEDERHOF A J. Bibliometric monitoring of research performance in the Social Sciences and the Humanities: A Review[J]. Scientometrics, 2006, 66(1): 81-100.

[13] WU Hao. Research trends of international river habitat based on bibliometrics[J]. Journal of Water Resources and Water Engineering, 2017, 28(4): 162-167.

[14] CAO Tianzheng, HAN Dongmei, SONG Xianfang, et al. Bibliometric analysis of research progress on surface water-groundwater interactions in coastal areas[J]. Advances in Earth Science, 2020, 35(2): 154-166.

[15] XIE Hao, LI Jun, ZOU Shengzhang, et al. Research status of groundwater pollution based on bibliometrics[J]. South-to-North Water Transfers and Water Science & Technology, 2021, 19(1): 168-178.

[16] LIU Yuyu, FENG Yuqing, JIANG Xin. Literature analysis of surface water-groundwater interaction research based on CiteSpace[J]. South-to-North Water Transfers and Water Science & Technology, 2022, 20(2): 218-229.

[17] LI Yali, ZHANG Hongjuan, YAN Haiqin, et al. Hotspots and trends of global agricultural production impacts on groundwater in recent 20 years[J]. Journal of Environmental Engineering Technology, 2022, 12(4): 1086-1095.

[18] WU Jian, WANG Min, JIN Zhihui, et al. Review and prospect of polycyclic aromatic hydrocarbons in soil environment: A bibliometric analysis based on Web of Science data[J]. Acta Pedologica Sinica, 2016, 53(5): 1085-1096.

[19] LI Jie, CHEN Chaomei. CiteSpace: Text mining and visualization in scientific literature[M]. Beijing: Capital University of Economics and Business Press, 2017.

[20] CHEN Chaomei. CiteSpace II: Detecting and visualizing emerging trends and transient patterns in scientific literature[J]. Journal of the American Society for Information Science and Technology, 2006, 57(3): 359-377.

[21] AN Xianjin, LI Wei. Research status and trends of international soil organic matter: A bibliometric analysis[J]. Chinese Journal of Soil Science, 2020, 51(2): 404-415.

[22] VIEUX B E. Geographic information-systems and nonpoint source water-quality and quantity modeling[J]. Hydrological Processes, 1991, 5(1): 101-113.

[23] DAHM C N, GRIMM N B, MARMONIER P, et al. Nutrient dynamics at the interface between surface waters and groundwaters[J]. Freshwater Biology, 1998, 40(3): 427-451.

[24] GROFFMAN P M, GOLD A J, SIMMONS R C. Nitrate dynamics in riparian forests: microbial studies[J]. Journal of Environmental Quality, 1992, 21(4): 666-671.

[25] BRUNKE M, GONSER T. The ecological significance of exchange processes between rivers and groundwater[J]. Freshwater Biology, 1997, 37(1): 1-33.

[26] ALA-AHO P, ROSSI P M, ISOKANGAS E, et al. Fully integrated surface–subsurface flow modelling of groundwater–lake interaction in an esker aquifer: Model verification with stable isotopes and airborne thermal imaging[J]. Journal of Hydrology, 2015, 522: 391-406.

[27] BAILEY R T, WIBLE T C, ARABI M, et al. Assessing regional-scale spatio-temporal patterns of groundwater-surface water interactions using a coupled SWAT-MODFLOW model[J]. Hydrological Processes, 2016, 30(23): 4420-4433.

[28] SPELDRICH B, GERLA P, TSCHANN E. Characterizing Groundwater Interaction with Lakes and Wetlands Using GIS Modeling and Natural Water Quality Measurements[J]. Water, 2021, 13: 983.

[29] SOULSBY C, MALCOLM I A, YOUNGSON A F, et al. Groundwater-surface water interactions in upland Scottish rivers: hydrological, hydrochemical and ecological implications[J]. Scottish Journal of Geology, 2005, 41: 39-49.

[30] BARON J S, HALL E K, NOLAN B T, et al. The interactive effects of excess reactive nitrogen and climate change on aquatic ecosystems and water resources of the United States[J]. Biogeochemistry, 2013, 114(1): 71-92.

[31] TANG Qiuhong. Global change hydrology: Terrestrial water cycle and global change[J]. Science China Earth Sciences, 2020, 63(3): 459-462.

[32] WU Songjun, TETZLAFF D, GOLDHAMMER T, et al. Hydroclimatic variability and riparian wetland restoration control the hydrology and nutrient fluxes in a lowland agricultural catchment[J]. Journal of Hydrology, 2021, 603: 126904.

[33] DU Zhipeng, SU Dechun. Bibliometric analysis of remediation technologies for heavy metal contamination in paddy fields[J]. Journal of Agro-Environment Science, 2018, 37(11): 2409-2417.

[34] XING Suzhi, LI Xiaoliang, XIAO Xin, et al. Research progress of organic fertilizer based on CiteSpace visualization analysis[J]. Soils, 2020, 52(4): 659-667.

[35] ZHAO Haili, ZHANG Jing. Research progress and hotspots of flood and drought disasters in China based on Citespace and Vosviewer[J]. Acta Ecologica Sinica, 2020, 40(12): 4219-4228.

[36] WAN Hongxiu, XUE Bin, GUO Ya, et al. Research trends of five major freshwater lakes in China: A bibliometric analysis based on WOS[J]. Journal of Water Resources and Water Engineering, 2018, 29(6): 8-18.

[37] PAN Yang, XI Yunguan, TIAN Wei, et al. Research status and hotspots of international organic agriculture biodiversity based on bibliometric analysis[J]. Journal of Agro-Environment Science, 2020, 39(7): 1429-1441.

[38] QIN Xiaonan, LU Xiaoli, WU Chunyou. Knowledge mapping of ecological security research in China: A bibliometric analysis based on Citespace[J]. Acta Ecologica Sinica, 2014, 34(13): 3693-3703.

[39] ZHANG Weirong, YAN Kang, WANG Haizhen, et al. Analysis of polycyclic aromatic hydrocarbon degradation genes and research progress based on bibliometrics from 1983 to 2019[J]. Acta Scientiae Circumstantiae, 2020, 40(3): 1138-1148.

[40] LIU Changming, LI Zongli, WANG Zhonggen, et al. Key scientific issues and research directions of river-lake water system connectivity[J]. Acta Geographica Sinica, 2021, 76(3): 505-512.

[41] FAN Wei, ZHANG Guangxin, LI Ranran. A review of research on surface water-groundwater interactions in wetlands[J]. Advances in Earth Science, 2012, 27(4): 413-423.

[42] WANG Wenke, LI Junting, WANG Wenming, et al. Estimating streambed parameters for a disconnected river[J]. Hydrological Processes, 2014, 28(10): 3627-3641.

[43] WANG Wenke, DAI Zhenxue, ZHAO Yaqian, et al. A quantitative analysis of hydraulic interaction processes in stream-aquifer systems[J]. Scientific Reports, 2016, 6(1): 19876.

[44] DU Yao, MA Teng, DENG Yamin, et al. Hyporheic zone hydrology-biogeochemistry: Principles, methods, and ecological significance[J]. Earth Science, 2017, 42(5): 661-673.

[45] VEIZAGA E A, OCAMPO C J, RODRÍGUEZ L. Hydrological and hydrochemical behavior of a riparian zone in a high-order flatland stream[J]. Environmental Monitoring and Assessment, 2018, 191(1): 10.

[46] MA Huiying, ZHU Guofeng, ZHANG Yu, et al. Ion migration process and influencing factors in inland river basin of arid area in China: a case study of Shiyang River Basin[J]. Environmental Science and Pollution Research, 2021, 28(40): 56305-56318.

[47] KONG Xiaole, WANG Shiqin, SHEN Yanjun, et al. Quantification of surface water and groundwater salinity sources in irrigated lowland area of North China Plain[J]. Hydrological Processes, 2021, 35(4): e14037.

[48] WANG Xiuyan, FEI Yuhong. Environmental Effect Caused by Over-exploitation of Deep Groundwater in North China[J]. Groundwater Science & Engineering, 2014, 2(1): 12-20.

[49] YUAN Ruiqiang, WANG Meng, WANG Shiqin, et al. Water transfer imposes hydrochemical impacts on groundwater by altering the interaction of groundwater and surface water[J]. Journal of Hydrology, 2020, 583: 124617.

[50] VICENTE E M, CARLOS D. Environmental Effects of Aquifer Overexploitation: A Case Study in the Highlands of Mexico[J]. Environmental Management, 2002, 29(2): 266-278.

[51] KABBOUR B B, ZOUHRI L, MANIA J. Overexploitation and continuous drought effects on groundwater yield and marine intrusion: considerations arising from the modelling of Mamora coastal aquifer, Morocco[J]. Hydrological Processes, 2005, 19(18): 3765-3782.

[52] WEI Xiaolu, BAILEY R T, ANONYMOUS. Using SWAT-MODFLOW to simulate groundwater flow and groundwater-surface water interactions in an intensively irrigated stream-aquifer system[C]. Washington, DC: American Geophysical Union, 2017.

[53] GAO Xubo, WANG Yanxin, WU Penglin, et al. Trace elements and environmental isotopes as tracers of surface water–groundwater interaction: a case study at Xin'an karst water system, Shanxi Province, Northern China[J]. Environmental Earth Sciences, 2009, 59(6): 1223.

[54] ZHANG Qian, WANG Wenke, DUAN Lei, et al. Numerical simulation of the impact of floodwater infiltration on groundwater regulation capacity in the Jinling River[J]. Journal of Water Resources and Water Engineering, 2014, 25(1): 91-94.

[55] JI Yuyu, SHI Wenqing, CHEN Qiuwen, et al. Temperature-tracing method for calculating flow velocity in the hyporheic zone of reservoir beaches[J]. Journal of Water Resources and Water Engineering, 2018, 29(3): 159-163.

[56] CANZIANI G A, FERRATI R M, ROSSI C, et al. The influence of climate and dam construction on the Ibera wetlands, Argentina[J]. Regional Environmental Change, 2006, 6(4): 181-191.

[57] BURNETT W C, WATTAYAKORN G, SUPCHAROEN R, et al. Groundwater discharge and phosphorus dynamics in a flood-pulse system: Tonle Sap Lake, Cambodia[J]. Journal of Hydrology, 2017, 549: 79-91.

[58] ZHOU Ziwen, ZHOU Zhifang, XU Haiyang, et al. Surface Water-Groundwater Interactions of Xiluodu Reservoir Based on the Dynamic Evolution of Seepage, Temperature, and Hydrochemistry Due to Impoundment[J]. Hydrological Processes, 2021, 35(8).

[59] YU Yang, LIU Yao, HUA Ting, et al. Research hotspots and trends of hydrological connectivity based on bibliometric analysis[J]. Journal of Water Resources and Water Engineering, 2021, 32(2): 1-9.

[60] JACKS G, NORRSTRÖM A. Hydrochemistry and hydrology of forest riparian wetlands[J]. Forest Ecology and Management, 2004, 196(2): 187-197.

[61] ZHAO Siyuan, JIA Yangwen, TANG Yingdong, et al. Study on groundwater recharge patterns in loess tableland areas based on stable isotopes[J]. China Rural Water and Hydropower, 2022(8): 63-69.

[62] ZHANG Zaiyong, WANG Wenke, WANG Zhoufeng, et al. Evaporation from bare ground with different water-table depths based on an in-situ experiment in Ordos Plateau, China[J]. Hydrogeology Journal, 2018, 26(5): 1683-1691.

[63] CAI Zizhao, WANG Wenke, ZHAO Ming, et al. Interaction between surface water and groundwater in Yinchuan Plain[J]. Water, 2020, 12(9): 2635.

[64] CAO Yongqiang, LU Jie. Current status and frontier analysis of meteorological drought research at home and abroad[J]. China Flood & Drought Management, 2021, 31(3): 1-7.

[65] ZHOU Xiaodan, ZHAO Guohui. Global liposome research in the period of 1995-2014: a bibliometric analysis[J]. Scientometrics, 2015, 105(1): 231-248.

[66] STROMBERG J C, RICHTER B, TILLER R. Effects of groundwater decline on riparian vegetation of semiarid regions: the San Pedro, Arizona[J]. Ecological Applications, 1996, 6(1): 113-131.

[67] WANG Zhan, WANG Wenke, ZHANG Zaiyong, et al. River-groundwater interaction affected species composition and diversity perpendicular to a regulated river in an arid riparian zone[J]. Global Ecology and Conservation, 2021, 27: e1595.

[68] XIN Pei, WILSON A, SHEN C J, et al. Surface water and groundwater interactions in salt marshes and their impact on plant ecology and coastal biogeochemistry[J]. Reviews of Geophysics, 2022, 60(1): e2021RG000740.

[69] WANG Fenfang, XIAO Kai, SANTOS I R, et al. Porewater exchange drives nutrient cycling and export in a mangrove-salt marsh ecotone[J]. Journal of Hydrology, 2022, 606: 127401.

[70] WANG Wenke, GONG Chengcheng, ZHANG Zaiyong, et al. Research status and prospect of groundwater hydrology and ecological effects in arid regions[J]. Advances in Earth Science, 2018, 33(7): 702-718.

[71] RAFIEI V, NEJADHASHEMI A P, MUSHTAQ S, et al. Groundwater-surface water interactions at wetland interface: Advancement in catchment system modeling[J]. Environmental Modelling & Software, 2022, 152: 105407.