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Use of Computerized Bibliometric Systems to Analyse 20-Year Trends in the Field of Environmental Groundwaters: An E-Programme Simulation Study

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***Abstract: -* Objective:** To map out the thematic areas, methodological approaches, and evolution of environmental groundwater research over 20 years, identifying key trends, collaborative networks, and emerging research clusters that have shaped the field. Identify trends in the field over the last 20 years to inform subsequent studies

Methods: Using CiteSpace 6.2.R2, a comprehensive bibliometric analysis was conducted on 2475 documents, focusing on keyword co-occurrence, clustering, and burst analysis. The study also examined co-authorship and co-citation networks to understand the structure and dynamics of the research community.

Results: The study identified several key research clusters, including Heavy Metals, Risk Assessment, and Pollution, indicating a focus on contamination effects and mitigation strategies. Innovative research areas like Self-Healing and Magnetic Resonance Sounding have emerged, highlighting advancements in materials and geophysical methods. The research has progressively integrated interdisciplinary methodologies, with recent trends emphasizing technological approaches like numerical simulation for enhancing groundwater management.

Conclusions: Over two decades, environmental groundwater research has evolved from basic contaminant studies to sophisticated, interdisciplinary approaches that integrate cutting-edge technologies. This progression underlines the increasing complexity and scope of challenges faced in groundwater management and suggests future directions involving more integrated and technologically driven solutions.

Keywords: Groundwater research, Environmental contamination, Bibliometric analysis, CiteSpace, Sustainable management.

I. Introduction

Environmental groundwater research has experienced substantial growth over the past two decades, revealing pivotal trends that hold significant implications for both ecological and human health [1-3]. As industries and populations expand, the resultant pressure on groundwater resources demands rigorous scientific scrutiny to develop effective management strategies. This study undertakes a comprehensive bibliometric analysis to explore the trends and hotspots in environmental groundwater research, focusing on the accumulation of knowledge and the evolution of research themes from 2003 to 2024 [4-6]. Our approach leverages the robust CiteSpace 6.2.R2 software to systematically analyze and visualize the data extracted from the Web of Science Core Collection database, ensuring a meticulous examination of the literature [7-10].

Central to the methodological framework of this study is the utilization of CiteSpace software, a powerful tool designed for visualizing and analyzing trends in scientific literature. The choice of CiteSpace is instrumental in enabling a nuanced exploration of complex bibliometric data, facilitating the identification of key patterns, trends, and structural shifts within the field of environmental groundwater research [11-13]. Through its sophisticated algorithms, CiteSpace generates visual representations of co-authorship, keyword co-occurrence, and citation networks, thereby providing a clearer understanding of the intellectual landscape and the evolution of research themes over time [14-16].

The significance of this study lies in its ability to elucidate the dynamic shifts in focus within the field, particularly as they relate to emerging contaminants and innovative remediation technologies [17-20]. By integrating co-authorship networks, keyword analyses, and co-citation mapping, this study not only highlights the most influential studies but also outlines the collaborative networks that underpin the scientific discourse in this area [21-24]. The findings from this analysis are expected to offer valuable insights into the research trajectories that have shaped the current landscape of environmental groundwater studies, as well as to identify future directions and potential gaps in the literature.

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This study aims to contribute to the foundational knowledge of environmental groundwater science, offering a scholarly lens through which researchers and policymakers can view the progression of the field [25-29]. By mapping out the thematic areas that have garnered the most attention and the methodologies employed, this study provides a crucial overview of the past two decades of research. This, in turn, sets the stage for future studies to build upon established knowledge, thereby enhancing the efficacy and sustainability of groundwater management practices globally.

II. Materials and Methods

2.1 Source of Materials

The literature review adhered to the principles of focusing on the frontiers and hot topics in the field of environmental groundwater research, and aimed to include as comprehensively as possible the relevant literature from this field. The inclusion covered domestic and international literature from the past 20 years, with the search timeframe set from January 1, 2003, to May 1, 2024. English-language literature was sourced from the Web of Science Core Collection database (WOSCC), using the search terms 'environment' (Topic) and 'underground water' (Topic), limited to the document types Article and Review.

Exclusion criteria for literature were as follows: (i) meeting abstracts, editorials, and other types of documents; (ii) documents clearly unrelated to environmental groundwater research; (iii) duplicated documents. Ultimately, 2,475 documents met the criteria for this study.

2.2 Research Methods

In this study, the valid literature collected was imported into the CiteSpace 6.2.R2 software. The data import timeframe was set from January 2003 to May 2024, with the time slicing option set to one year intervals. Analyses conducted included co-authorship network analysis, keyword analysis, and co-citation analysis; the results were visually processed and corresponding scientific knowledge maps were drawn. Additionally, a comparative literature analysis was conducted to explore the differences and similarities in the hot topics and development trends of environmental groundwater research over the past 20 years.

III. Result

3.1 Analysis of Research Hotspots

3.1.1 Keyword Co-occurrence Analysis

The keyword co-occurrence map reflects the research hotspots in the field and the evolution of these hotspots, as shown in Figure 1. Each node in the map represents a keyword, where the size of the node indicates the frequency of occurrence of the keyword and the span of time; the lines between nodes reflect the collaborative relationships and closeness between keywords in the field.

The top 10 keywords by frequency of appearance in the literature are listed in Table 1. Specific keywords such as 'model,' 'behavior,' 'performance,' 'heavy metals,' and 'evolution' are hotspots in the research field. It is evident that in the past two decades, research in the field of environmental groundwater has primarily focused on heavy metal pollution and the use of various predictive models to assess groundwater contamination.

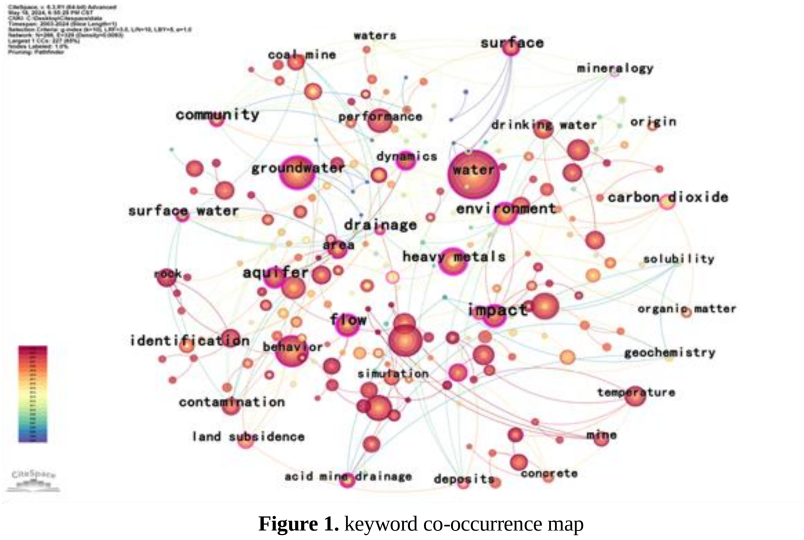

Figure 1. keyword co-occurrence map

Table 1: Top 10 keywords by frequency of appearance in the literature

No.	frequency	Degree of intermediary centrality	Year	Keyword
1	261	0.17	2003	water
2	107	0.22	2004	groundwater
3	100	0.04	2009	model
4	89	0.16	2014	behavior
5	66	0.08	2016	performance
6	66	0.24	2008	environment
7	62	0.04	2008	soil
8	61	0.3	2007	heavy metals
9	59	0.03	2007	system
10	52	0.06	2013	evolution

3.1.2 Keyword Clustering Analysis

Keyword clustering analysis simplifies the network of keyword co-occurrences into a smaller number of clusters through statistical clustering methods. The Log-likelihood Ratio (LLR) algorithm is employed for clustering analysis of keywords, with the resulting keyword cluster map displayed in Figure 2. After clustering, ten clusters are formed; a smaller cluster number indicates a higher concentration and greater number of keywords within that cluster. The modularity Q value of the keyword clusters is 0.8544, which is greater than 0.8, indicating that the network structure of the cluster map is significantly modular and the clustering is effective. The average silhouette score (S) is 0.933, exceeding 0.8, suggesting high homogeneity and convincing clustering results, with both homogeneity and the credibility of the clustering outcomes positively correlated with the average silhouette value.

The cluster analysis primarily spans nine clusters, reflecting diverse aspects of groundwater research: Heavy Metals (#0): Central to studies investigating the accumulation and impact of heavy metals in groundwater, this cluster includes research on contamination sources, migration patterns, and remediation technologies.Risk Assessment (#1): This cluster focuses on methodologies and models used to evaluate the risk associated with groundwater pollution, including assessment of health risks to human populations.Magnetic Resonance Sounding (#2): Emphasizes the use of geophysical methods, particularly magnetic resonance, for groundwater exploration and aquifer characterization.Self-Healing (#3): Studies in this cluster discuss innovative materials and technologies that promote self-healing properties in groundwater systems, aimed at natural recovery and sustainability.Deposits (#4): This cluster deals with geological studies on groundwater deposits, including their formation, characteristics, and impacts on water quality.Bacterial (#5): Focuses on the microbiological aspects of groundwater, including the role of bacteria in bioremediation, biofiltration, and natural purification processes.Water (#6): Encompasses a broad range of studies on water management, hydrological cycles, and sustainable usage in relation to groundwater resources.Pollution (#7): Targets studies related to various pollution sources, impacts on ecosystems, and approaches for pollution control and mitigation in groundwater.Pore Structure (#8): Investigates the physical properties of soil and rock, including porosity and permeability, which affect groundwater flow and storage.Acid Mine Drainage (#9): Concerns research on the effects of mining activities on groundwater, particularly the formation and management of acid mine drainage.

Over the past two decades, the field of environmental groundwater research has evolved significantly, characterized by a multidisciplinary approach and the integration of advanced technologies. The analysis of keyword co-occurrence across our dataset indicates a dynamic expansion in the thematic areas of study, underpinned by a growing recognition of groundwater's critical role in global ecological and human health frameworks. The emergence of clusters such as Heavy Metals, Risk Assessment, and Pollution highlights an acute focus on the adverse effects of contaminants and the imperative for robust evaluation and mitigation strategies. Concurrently, innovative research areas like Self-Healing and Magnetic Resonance Sounding reflect the progressive adoption of novel materials and geophysical techniques aimed at enhancing the resilience and characterization of aquifer systems. The intersectionality of these clusters underscores a trend towards holistic and sustainable groundwater management practices, emphasizing restoration, pollution prevention, and scientifically informed risk management. This shift not only mirrors the escalating environmental challenges posed by industrialization and urbanization but also aligns with global sustainability goals aimed at safeguarding water resources for future generations.

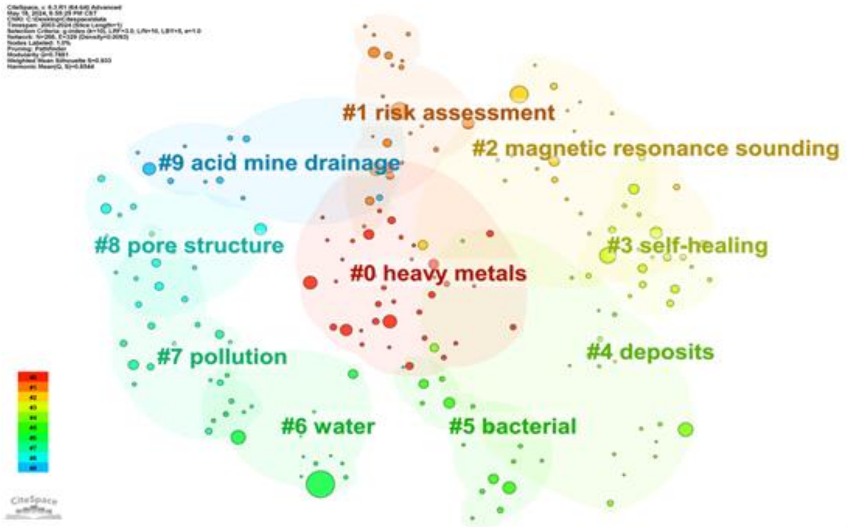

Figure 2. Keyword clustering analysis map

3.1.3 Keyword Burst Analysis

Burst keywords are those that see a sudden increase in citation frequency within a specific time period, reflecting the research trends during that interval. The greater the burst intensity of a keyword, the more it represents the term as an active term in the field during that time. The top 15 keywords with the strongest bursts in the field of environmental groundwater research are shown in Figure 3.

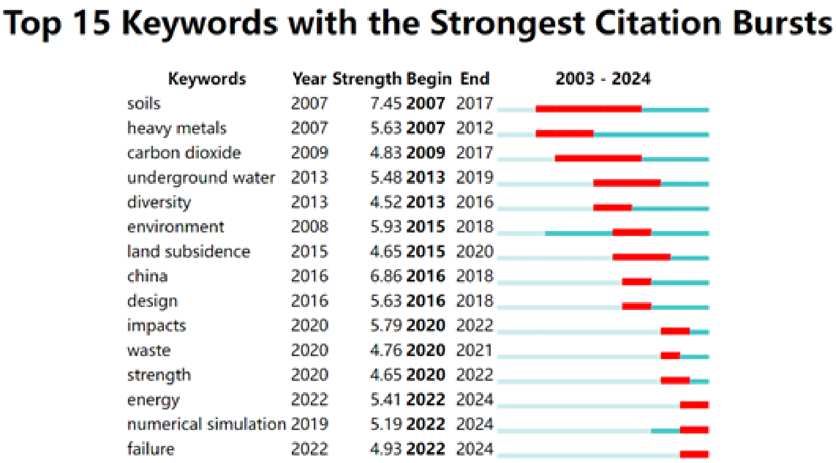

Figure 3. The top 15 keywords map

The Keywords popping up map for environmental groundwater research,outlines the dynamic shifts and focal transitions in keyword popularity over two decades. Initially, prominent keywords such as "soils" and "heavy metals" highlight early concerns centered on soil contamination and the persistent presence of heavy metals in groundwater systems, a reflection of the ongoing global challenge of industrial pollutants affecting water quality from 2007 to 2017. Around 2009, the focus expands to "carbon dioxide" and its implications in underground water systems, indicative of the growing interest in understanding the interactions between greenhouse gases and geological formations. From 2013 onwards, research keywords like "underground water" and "diversity" begin to capture the broader scope of groundwater studies, emphasizing the complex ecosystems involved and the varied methodologies employed to assess water quality and sustainability. The recent surge in keywords such as "numerical simulation" and "failure" from 2019 to 2024 suggests a technological pivot in the field, where digital modeling and the analysis of system failures have become critical in predicting and managing groundwater resources efficiently. This trajectory from foundational environmental concerns to advanced technological applications illustrates the evolving landscape of groundwater research, which now incorporates a sophisticated array of scientific tools and theoretical frameworks to tackle both longstanding and emergent environmental challenges.

The evolution of environmental groundwater research over the past two decades can be distinctly segmented into four developmental stages:

Early Phase (2003-2009): During the initial years, research predominantly centered on the impacts of soil contamination and the presence of heavy metals within groundwater systems, reflecting acute concerns about the environmental consequences of industrial activities on water quality. Keywords like "soils" and "heavy metals" were notably prevalent, illustrating the field's focus on these fundamental issues.

Middle Phase I (2009-2013): This period marked a transition towards broader environmental interactions, with significant attention given to "carbon dioxide" and its underground interactions. The emphasis here was on understanding how greenhouse gases and other environmental parameters interact with geological formations, signaling a shift towards more integrated environmental studies.

Middle Phase II (2013-2019): Research keywords such as "underground water" and "diversity" began to dominate, indicating a diversified approach towards groundwater studies. This stage expanded the scope to include various aspects of ecosystem complexity and methodological diversity, focusing on sustainable management and qualitative assessments of groundwater ecosystems.

Recent Phase (2019-2024): The most recent stage reflects a technological and methodological shift, with "numerical simulation" and "failure" emerging as key areas of focus. This phase is characterized by the adoption of advanced digital tools to model groundwater systems and address failures more predictably. This transition highlights a move towards leveraging technology to enhance the efficacy and precision of groundwater management and sustainability efforts.

Each stage demonstrates the field's progression from addressing immediate contamination issues to embracing advanced technologies and methodologies, underscoring a dynamic shift towards a more sophisticated and holistic approach to groundwater research.

3.2 Collaborative Network Analysis

Collaborative network analysis is beneficial for identifying the social relationships between countries, institutions, or authors within a field and for assessing their influence. This analysis provides a clearer understanding of the academic activities, research background, and organizational structures in the field of environmental groundwater research.

3.2.1 National Collaboration Network Analysis

The national collaboration map is shown in Figure 4. The top five countries in terms of the number of publications are China (803 publications), the United States (257 publications), Poland (135 publications), France (126 publications), and Italy (120 publications). China accounts for 32.44% of the total publications, which is greater than the combined total of the countries ranked second to fifth, indicating China's significant academic contributions and a high position in collaborative efforts within this field. Although China ranks first in terms of publication volume in the field of environmental groundwater research, its centrality is less than 0.1, reflecting the need for deeper and strengthened academic collaboration within the field. From 2019 to 2023, China demonstrated the strongest citation impact of articles, indicating that in the past five years, Chinese researchers have conducted extensive research on environmental groundwater and are likely to continue to intensify their exploration and research in this field in the future.

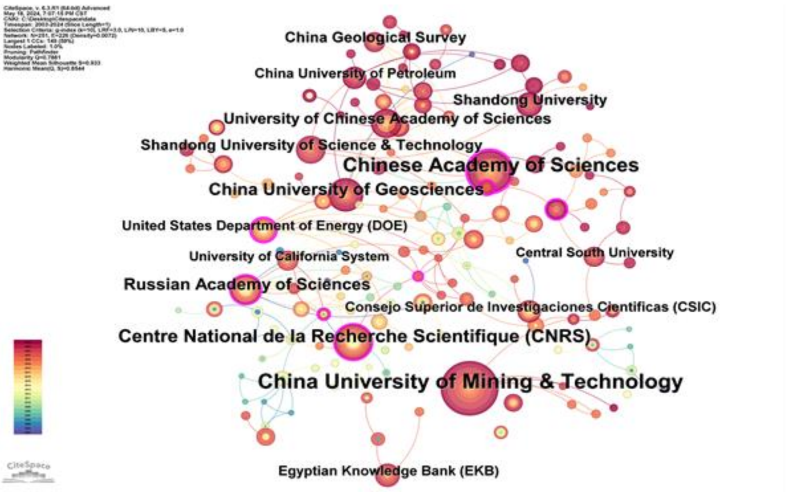

Figure 4. National collaboration map

3.2.2 *Institutional and Author Collaboration Network Analysis*

The institutional collaboration network is shown in Figure 5, and the author collaboration network is shown in Figure 6. The institutional network is complex, with densely distributed institutions and numerous connections between nodes, but few nodes representing individual institutions. This indicates that the institutions are closely connected, with frequent collaborations, primarily domestic within each country, with less international cooperation. In the author collaboration map, although the distribution of authors is relatively scattered, the connections between them are tight, for example, Arulrajah Arul and Liu Shiliang have formed a closely collaborating sub-network. Other teams, while also forming certain internal cooperation networks, have less interaction among them, suggesting an urgent need to strengthen collaboration among scholars in the field of environmental groundwater research.

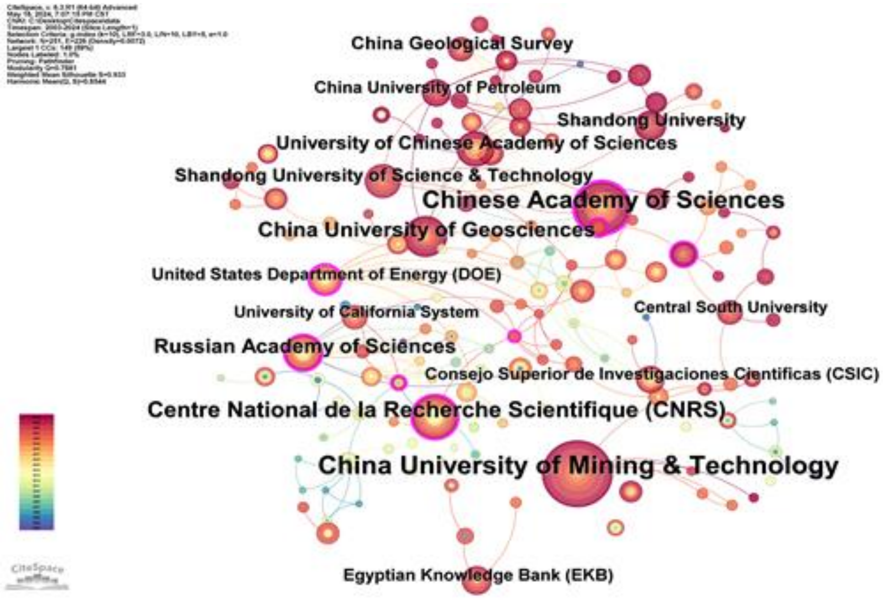

Figure 5. Institutional collaboration network map

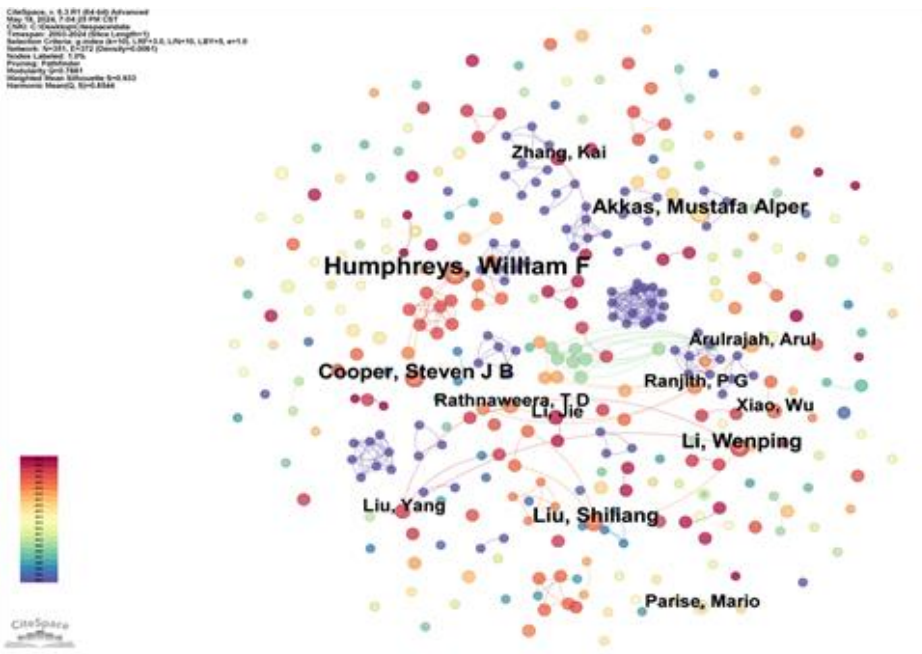

Figure 6. author collaboration network map

3.3 *Co-citation Analysis*

Co-citation analysis, a method to measure the relationship between documents, serves as a foundation for tracing the development of a field. High co-citation rates indicate foundational research within a domain. The co-citation map is displayed in Figure 7. Through the analysis of co-cited documents, it is evident that English-language documents in the following five areas have high citation volumes, potentially representing key articles leading the research hotspots in the field:(1)Advanced Contaminant Modeling: As indicated by the growing emphasis on "numerical simulation," research is likely to increasingly focus on the development and refinement of computational models to predict contaminant behavior, migration patterns, and interactions within groundwater systems. (2) Groundwater System Resilience: Keywords like "self-healing" and recent trends in sustainability studies suggest that future research will explore materials and technologies that enhance the natural resilience of groundwater systems. This includes the ability of aquifers to recover from pollution events autonomously. (3)Impact of Climate Change on Groundwater: The prominence of "carbon dioxide" and "energy" in recent years points towards a significant research trajectory addressing the impacts of climate change on groundwater resources. This includes studies on greenhouse gas sequestration, temperature effects on water quality, and hydrological cycle alterations. (4) Technological Innovations in Pollution Detection: With "failure" and "strength" emerging as recent keywords, there is likely a shift towards exploring new technologies and methodologies for detecting and quantifying pollutants in groundwater, including real-time monitoring systems and advanced analytical tools. (5) Comprehensive Risk Assessment Strategies: The consistent focus on "risk assessment" across years underscores an ongoing need to develop more comprehensive, predictive, and system-oriented approaches to assessing the risks associated with groundwater pollution, particularly in terms of human health and ecological impacts.

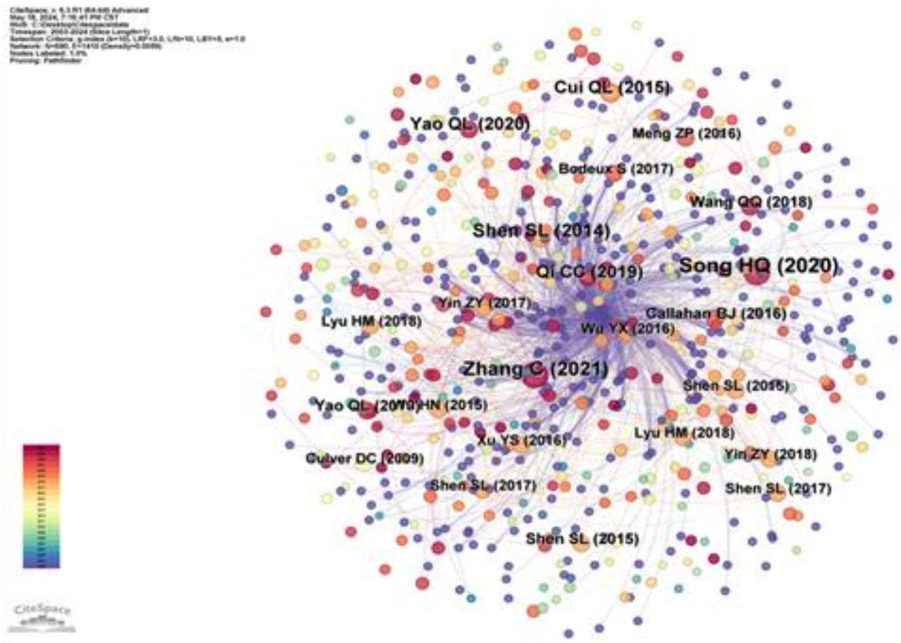

Figure 7. co-citation map

IV. DISCUSSION

In this scholarly exploration of environmental groundwater research over the past two decades, we have illuminated significant developmental trajectories and methodological innovations, framed by our robust bibliometric analysis using CiteSpace software. The central findings underscore a shift from basic contaminant studies to sophisticated, interdisciplinary approaches integrating cutting-edge technologies for aquifer system analysis and sustainable management practices [30-33]. The emergence of keyword clusters such as Heavy Metals, Risk Assessment, and Pollution reveals an intensified focus on the mechanisms of contamination and the development of effective mitigation strategies. Meanwhile, innovative clusters like Self-Healing and Magnetic Resonance Sounding reflect a growing inclination towards employing novel materials and techniques to enhance the natural resilience of groundwater systems. This study not only charts a historical progression of research themes but also captures the essence of current scientific inquiry and collaborative efforts in the field. These insights are critical for policymakers and researchers aiming to navigate the complexities of groundwater sustainability and ecological preservation in the face of escalating global environmental challenges [34-36]. The detailed examination of collaboration networks and co-citation maps further enriches our understanding of the academic landscape, highlighting both the achievements and areas necessitating more in-depth exploration and international cooperation.

Looking ahead, the field of environmental groundwater research is poised to evolve significantly, reflecting the urgent need for advanced and integrative approaches in addressing the challenges of groundwater management and sustainability [37-40]. Future trends will likely emphasize the expansion of interdisciplinary methodologies that merge hydrological sciences with emerging technologies such as artificial intelligence and big data analytics. This integration is expected to enhance the precision and efficiency of groundwater assessments and remediation strategies. There will be an increased focus on the implications of climate change on groundwater resources, necessitating comprehensive studies on the interactions between groundwater systems and changing global climate patterns [41-44]. Innovative materials and technologies that promote the resilience and self-healing capacities of aquifers are also anticipated to gain prominence, supporting sustainable water management practices. The growing concern for public health and ecological impacts will drive more rigorous risk assessments and the development of regulatory frameworks tailored to ensure the safety and sustainability of groundwater resources [45-48]. Collaborative international research and the standardization of methodologies are likely to intensify, fostering a global approach to groundwater challenges [49-50]. These trends underscore a shift towards a more holistic and scientifically robust framework for managing the planet's vital groundwater reserves.

While this bibliometric analysis provides comprehensive insights into the field of environmental groundwater research, several limitations need to be acknowledged. Firstly, the scope of the literature reviewed was confined to the Web of Science Core Collection database, potentially omitting relevant studies indexed in other databases such as Scopus or Google Scholar, which might offer additional perspectives or data. Secondly, despite meticulous efforts to encompass a broad array of research topics through our search strategy, the inherent limitations of keyword-based searches may have restricted the inclusion of all pertinent studies, particularly those that utilize less common terminology or focus on emerging research areas. Lastly, the reliance on CiteSpace for data visualization and analysis, while facilitating the identification of trends and collaborations, may not fully capture nuances that could be gleaned from a full-text review, possibly skewing the interpretation of data or underrepresenting less prominent but equally significant research threads.In future studies we will further address the shortcomings of this study by expanding the search, reducing bias and cross-validation.

V. Conclusion

The comprehensive bibliometric analysis presented in this article offers a nuanced exploration of the evolving landscape of environmental groundwater research over the past two decades, using CiteSpace software to elucidate pivotal trends and shifts in research focus. Central findings highlight a significant progression from basic studies on contaminant impacts to sophisticated, interdisciplinary approaches that incorporate cutting-edge technologies for detailed aquifer system analysis and sustainable management. Emerging research clusters such as Heavy Metals, Risk Assessment, and Pollution emphasize the intensified examination of contamination mechanisms and the development of robust mitigation strategies. Meanwhile, innovative themes like Self-Healing and Magnetic Resonance Sounding indicate a shift towards leveraging novel materials and advanced geophysical techniques to enhance the natural resilience and characterization of groundwater systems. The integration of diverse methodologies points towards a future direction focused on merging hydrological sciences with technological innovations like AI and big data, aimed at improving the precision of groundwater evaluations and fostering sustainable management practices globally.

VI. Data Availability

The data used to support the findings of this study are included within the article.

VII. Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

VIII. Acknowledgement

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