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RESEARCH

Trends and frontiers in coal mine groundwater research: insights from bibliometric analysis

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Abstract Globally, studying the impact of coal mining on groundwater remains challenging. This is because the exploitation of coal resources and the sustainable development of groundwater resources involve economic, social, and environmental aspects. Over the last few decades, the number of publications on groundwater-related studies in coal mining areas has increased. However, they are not currently reviewed in a widely visible manner through bibliometric analyses. This study investigated groundwater research in coal mining areas worldwide using scientometric analysis based on 1196 articles from the Web of Science database to provide a global perspective and gain quantitative insight into research frontiers and trends in the field by mapping existing knowledge. We analyzed the key contributors and development processes of coal mine groundwater research and identified four research frontiers based on scientometric mapping results with an understanding of the research field: numerical modeling, conceptual modeling and mechanisms, feedback mechanisms between anthropogenic-environmental systems and groundwater systems, ground subsidence management, groundwater quality evaluation and risk assessment, and groundwater resource management in coal mines. Finally, we summarize the current challenges and propose methods to promote the green mining of coal resources and the sustainable development and management of groundwater resources.

Highlights

- In this study, 1196 articles from the Web of Science database were reviewed.
- This study investigated groundwater research in coal mining regions worldwide.
- Five research frontiers were identified.
- We suggest solutions to encourage environmentally friendly coal mining.
- We suggest measures for the sustainable management of groundwater resources.

Keywords Coal mines · Groundwater · Bibliometric analysis · Green mining · Sustainable groundwater management

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1 Introduction

Globally, the contradictions and conflicts between mining and water resources remain a challenge (Jiang et al. 2015; Northey et al. 2016; Mudd 2008; Wu and Wang 2006; Abiye et al. 2011). Coal is the primary source of energy in many countries (Prakash et al. 2020; Wang et al. 2020), and coal mining promotes economic and social development. However, it can also change the groundwater flow system and the structure of the hydrogeological system, resulting in substantial and long-term impacts on local or regional hydrological processes, groundwater resources, ecology, and the geological environment in coal mining areas (Younger et al. 2002; Newman et al. 2017; Moya et al. 2014; Zhang et al. 2022; Adam and Paul 2000; Jordan 2009; Chiew et al. 2018; Tiwary 2001; Wu et al. 2006; Singh et al. 2013; Bell et al. 2006; Yang et al. 2022; Martins et al. 2022; McNally and Evans 2007). Research on groundwater in coal mining areas is well documented worldwide (Abiye et al. 2011; Chabukdhara and Singh 2016; Cravotta 2015; Qu et al. 2021, 2022; Banks et al. 2017; Afonso et al. 2019; Adhikary and Guo 2015; David et al. 2017), such as hydrogeological effects (Zhang 2005; Yang et al. 2020; Booth 2002, 2007), quantity assessment of groundwater resources (Tang et al. 2021; Guo et al. 2019; Kamenopoulos et al. 2018), groundwater quality and risk evaluation (Masood et al. 2020; Mhlongo et al. 2018; Dom et al. 2016), groundwater pollution and management (Acharya and Kharel 2020; Akcil and Koldas 2006), and ecological and geo-environmental aspects (Karan et al. 2019; Sepehri et al. 2017; Martins et al. 2022). The sustainable development of coal mining must be balanced among environmental, economic, and social aspects (Friesen et al. 2017; Prakash et al. 2020; Kemp et al. 2010; Lee 2014; Younger et al. 2005; Wirth et al. 2018; Hu et al. 2015; Zeng et al. 2016), and Several countries have gradually adopted legislative measures for this purpose (Kemp et al. 2010; Wu et al. 2006).

In recent years, some scholars have used modeling and data-driven approaches (Sun et al. 2022) to analyze the impact of human activities associated with mining (coal mining) and climate change on hydrological time series (Chiew et al. 2018) to reveal the response of hydrological processes (Evans et al. 2015).Conceptual models, mathematical models, and data-driven hydrologic approaches remain the mainstream methods for analyzing mining-induced hydrogeologic response processes (Guo et al. 2019; Delottier et al. 2017; Moya et al. 2014; Zhu et al. 2020). Although significant research has been conducted to address issues related to coal mining and groundwater, researchers from different disciplines have produced important literature reviews on their specific issues or directions of interest to summarize key findings in specific aspects (Yang et al. 2022; Acharya and Kharel 2020; Welch et al. 2021; Jiang et al. 2020; Prakash et al. 2020; McCay et al. 2018). Yang et al. (2022) conducted a global meta-analysis on the watershed scale to investigate the mixed effects of coal mining on soil and water conservation. They suggested that soil infiltration processes disrupt surface hydrological cycling processes and that soil erosion from coal mining can be buffered if appropriate coal mining practices and revegetation measures are adopted. Acharya and Kharel (2020) summarized acid mine drainage (AMD) issues, prediction, and control methods, key research gaps, challenges, and opportunities. They suggested that prevention techniques and integrated management can minimize AMD risks, and that mining and AMD research can benefit from the use of emerging drones and hyperspectral imaging technologies for hydrogeochemical surveys of active and abandoned mines. Welch et al. (2021) provided a comprehensive critical review of global understanding of geochemistry (e.g., sources and COI transport rates) and hydrology (e.g., water balance and water transport) of abandoned or operating coal mine tailings and waste dumps. Subsequently, their implications for ecosystems and human health and made recommendations for future research. Jiang et al. (2020) developed a conceptual model for the influence of extraction zone water on the karst water-surface water environment by reviewing the distribution, characteristics, and formation of water in coal mine extraction zones in karst areas in China. However, such investigations may have overlooked broader frontiers and trends in groundwater research in coal mining areas.

As the number of publications increases, it is a need to apply data science and visualization techniques to gain access to the entire body of scientific knowledge in a particular research area and identify research frontiers and hotspots (Aria and Cuccurullo 2017). Scientometric mapping is increasingly used in science as a popular method to help researchers sort through existing knowledge bases; identify research hotspots, trends, opportunities, and challenges in terms of country, author, multidisciplinarity, citations, and keywords; and gain quantitative insights into the development of research in specific areas of scientific investigation (Jinshui et al. 2012; Aria and Cuccurullo 2017; Chen 2014). CiteSpace is a commonly used Java-based statistical and visualization tool (Chen 2014). This study statistically reviews coal mining and groundwater research through a bibliometric analysis to gain a more comprehensive global perspective on this discipline. Based on this, future groundwater research frontiers and challenges can be identified in coal mining areas. Therefore, this study aimed to: (1) describe the results of the systematization and visualization of the database of groundwater research related to coal mining, (2) present current groundwater research frontiers and trends in coal mining areas, and (3) provide insights, future challenges, and recommendations for the sustainable development of coal mining and groundwater resources.

2 Methods

Figure 1 shows the framework diagram of this study, including data collection, parameter identification, analysis processes, identification of research frontiers and challenges, and prospects and suggestions.

2.1 Data collection and parameter determination

Literature was collected from the WoSCC database using the keywords “coal mine” and “groundwater*”, the category “topic” and the period “2000–2023.” The database was updated on March 5, 2023. The WoSCC database was chosen because it is an influential multidisciplinary database of scholarly abstracts and citations, the publications must be peer-reviewed, and it is also a qualified data source for bibliometric analysis. In this study, we only selected the publication type “article” and the articles in English language.

We used the CiteSpace 6.1 R6 (Chen 2014) and the Bibliometrix R package (3.1.4) (Aria and Cuccurullo 2017) to conduct the analyses. The Bibliometrix R package was used to analyze the influence of authors, countries, and journals. The CiteSpace software was used for the analysis and visualization of collaboration networks (author institution, country, and collaboration networks), influence networks (author co-citation), and keyword co-occurrence and burst analysis. The CiteSpace software

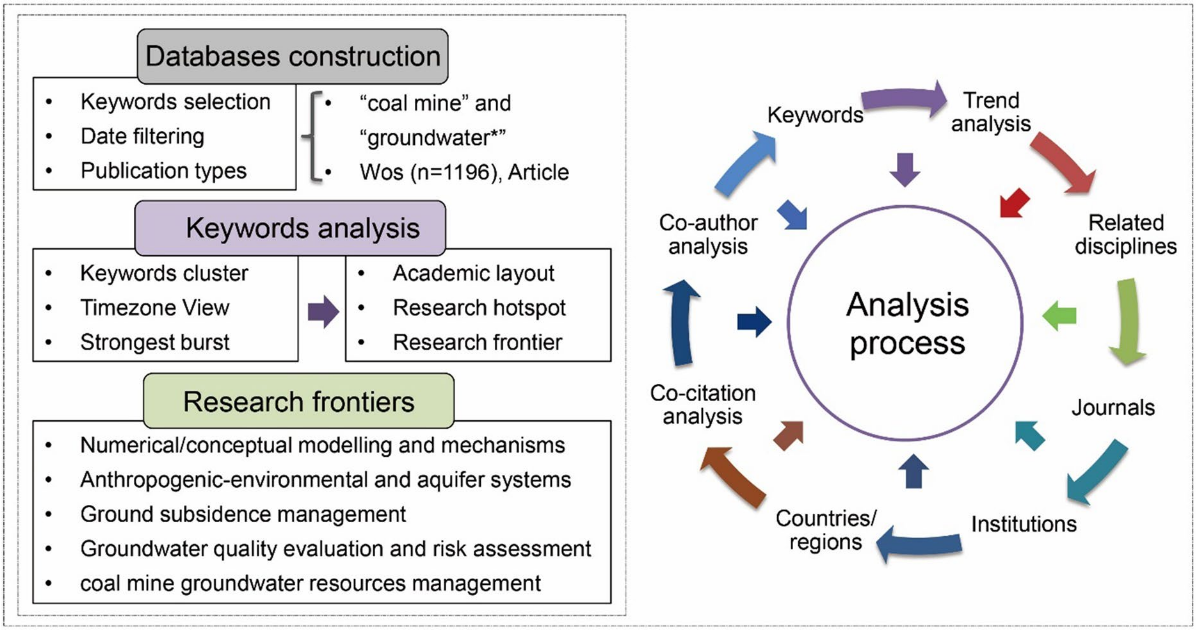


Fig. 1 The procedures of bibliometric analysis in this study

Table 1 Selection criteria in CiteSpace for scientometric analysis

Criteria category	Criteria
Node selection	g-index, topN
k value	25
Link Retaining Factor (LRF)	– 1
Maximum Links Per Node (L/N)	10
Parameter e	1.0
Cluster algorithm	Log-likelihood rate (LLR)
Pruning algorithm	Pathfinder, Pruning the merged network

parameters are listed in Table 1. The definitions of the parameters can be found in the CiteSpace user manual (Chen 2014). CiteSpace creates citation analyses that require algorithms based on different models, such as the Top-N and g-index. Both could select important publications. In this study, we chose the g-index algorithm to analyze author collaboration. Other analyses, such as country, institution, author co-citation, and keyword co-occurrence, were based on the Top-N algorithm. The Top-N was defined by selecting the N articles most cited in a given period. The "g-index" measures the research output of the researcher as an individual. This compensates for the h-index not reflecting the number of highly cited articles.

2.2 Analysis process, research frontier determination, issues, perspectives, and suggestions

Bibliometrix, CiteSpace, Microsoft Excel, and Origin were used for bibliometric analysis and data display. In the keyword analysis, we manually removed "coal mine" and "groundwater" from the keyword list, as well as some keywords that had no real meaning, such as "area." These search terms can interfere with keyword frequency statistics and clustering analysis results. Here, we explain the meaning of the CiteSpace software parameters for the creation of graphics in a uniform manner. The node size represents the number of articles in an object, and the thickness of the connecting lines between nodes represents the co-occurrence frequency. The color represents the time scale, and a darker color indicates earlier articles. The purple circle outside the node is central, which represents the concentration of more connection lines around that node. For each node, the inner parts refer to older articles, whereas the outer parts refer to newer articles. Ring thickness in a node is proportional to the number of articles in a given time slice. After the analysis process, the research frontiers were further identified by analyzing the keyword co-occurrence and clustering results for different periods (2000–2023 and 2018–2022), investigating the entire literature database, and combining our understanding and experience of current groundwater research in relation to coal mining. Issues were identified through an in-depth interpretation and comparison of the analysis results; presenting targeted developments and recommendations for future mining-related groundwater research.

3 Results and discussions

3.1 Temporal trend analysis

The number of publications on groundwater research in coal mines has increased over the last 20 years (Fig. 2d). As shown in Figs. 2a–c, China (719) has contributed significantly to groundwater research over the past decade in terms of the number of publications. This is followed by the USA (134) and Australia (70). Australia's interest in this field has increased significantly notably since 2012 (Fig. 2c). As shown in Fig. 2d, growth fluctuated between 2011 and 2017 and the mean number of publications was 49.7. During the last five years (2018–2022), the number of articles experienced explosive growth, with an average of 138.4 and reaching 177 in 2022. Articles published between 2018 and 2022 represent 57.9% of the total literature. This significant increase is an indication of the growing interest in coal mining and groundwater research and the development of new technologies and methods in the last five years. Specifically, in the coal mining field, the increase in groundwater-related research is a response to the threat of coal resource extraction to groundwater and geological environments. However, with the development of technologies (e.g., remote sensing, geographic information system (GIS), and artificial intelligence) and interdisciplinarity (land use and ecosystem restoration), multidisciplinary convergence

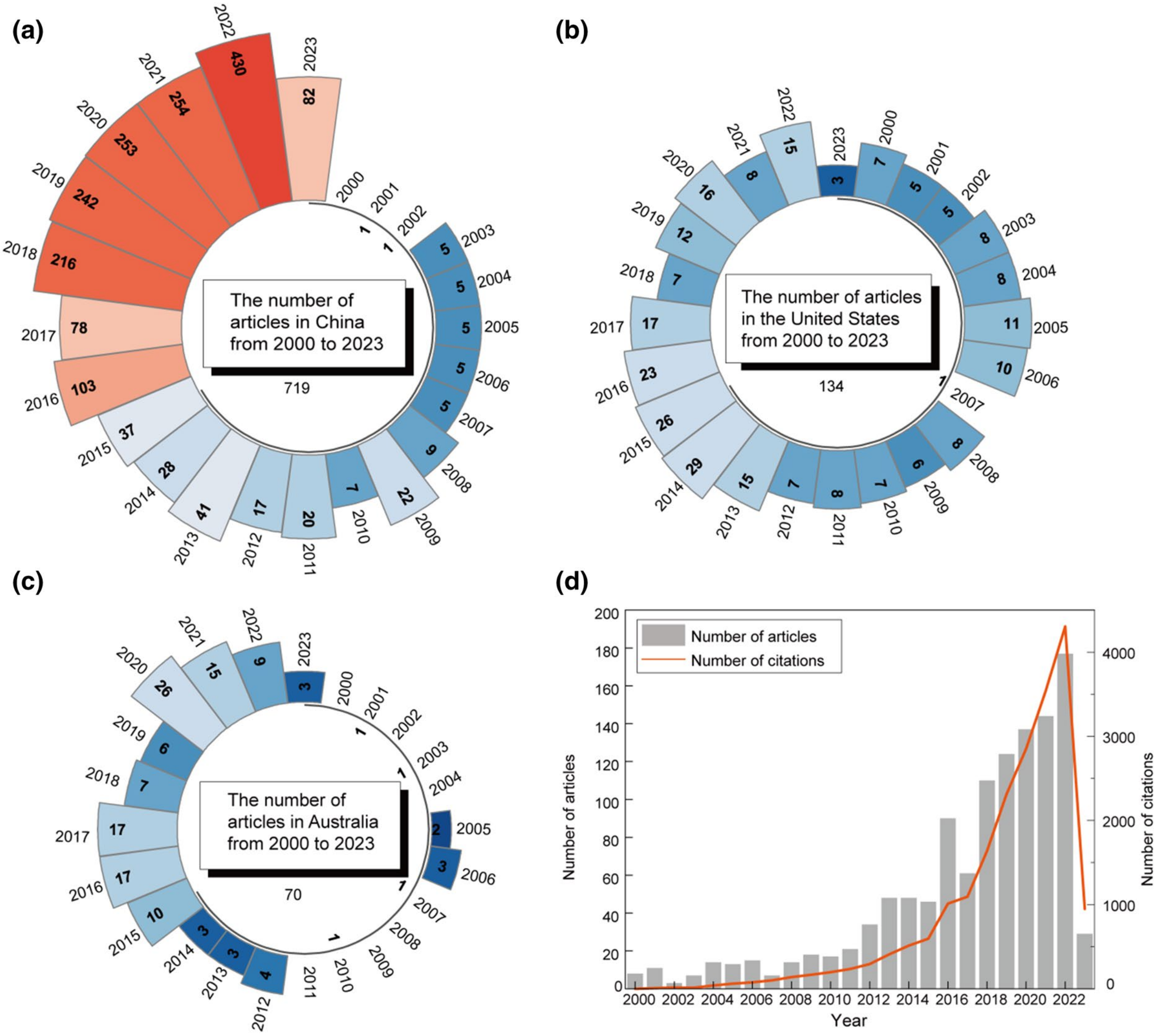


Fig. 2 Trends in publication output of articles on coal mine groundwater research from 2000 to 2023. **a** China; **b** USA; **c** Australia and **d** temporal variation of the total number of articles in the literature database

and innovation have contributed to a cost-effective and accurate approach to groundwater-related research in coal mines (Zhang et al. 2022; Vervoort and Declercq 2017; Yin et al. 2018; Hu et al. 2015; Malekzadeh et al. 2019).

3.2 Related disciplines

There is a wide range of disciplines and a high level of interdisciplinarity in groundwater research related to coal mining. As shown in Fig. 3, which shows the top 15 related disciplines, 1196 articles belong to 76 disciplines. Environmental Science (26%), Water Resources (22%), and Multidisciplinary Geosciences (20%) are the top three disciplines for groundwater research in coal mines, accounting for 68% of the total disciplines in the literature database. This reflects the increased research by scholars on the development of coal resources in relation to water resources and environmental issues. Other disciplines, such as geochemistry and geophysics, energy and fuels, engineering environment, civil engineering, engineering geology, green, and sustainable science and technology, contribute to the development of groundwater research

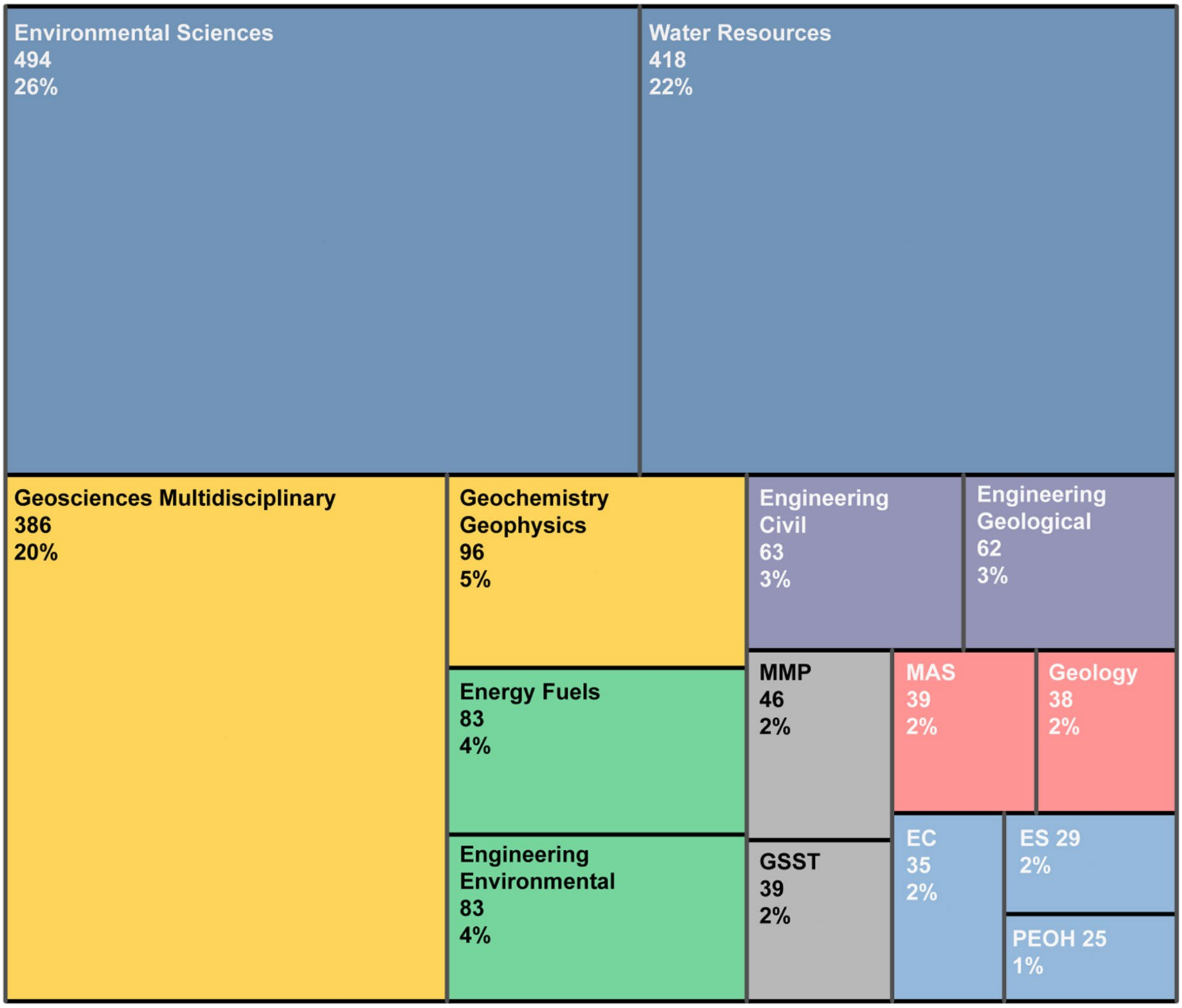


Fig. 3 Numbers of articles in related disciplines (top 15). Data are collected from Web of Science. (MMP: Mining Mineral Processing; MAS: Meteorology Atmospheric Sciences; EC: Engineering Civil; ES: Environmental Sciences; GSST: Green Sustainable Science Technology; PEOH: Public Environmental Occupational Health)

in coal mines. This shows that the disciplines of geophysics, energy, environmental engineering, and engineering technology have been applied to groundwater research in coal mining, which corresponds to research hotspots in mining and safety engineering in recent years. Furthermore, the development and application of geophysical exploration technology, mining technology, and water conservation have been considered. Almost half of the articles belonged to the Environmental Sciences (493) and the Water Resources (418). Groundwater research associated with coal mining also supports the development of interdisciplinarity, as shown in Fig. 3. (e.g., Meteorology and Atmospheric Sciences, Public Environmental Occupational Health), which reflects the close intersection between "Green Mine" and other disciplines. These interdisciplinary disciplines represent current trends and possible future developments of global groundwater-related research in coal mines, which provide a disciplinary guide to achieve the "Green Mine" development goals worldwide. Research on groundwater related to mining activities will continue to develop with the trend of interdisciplinarity.

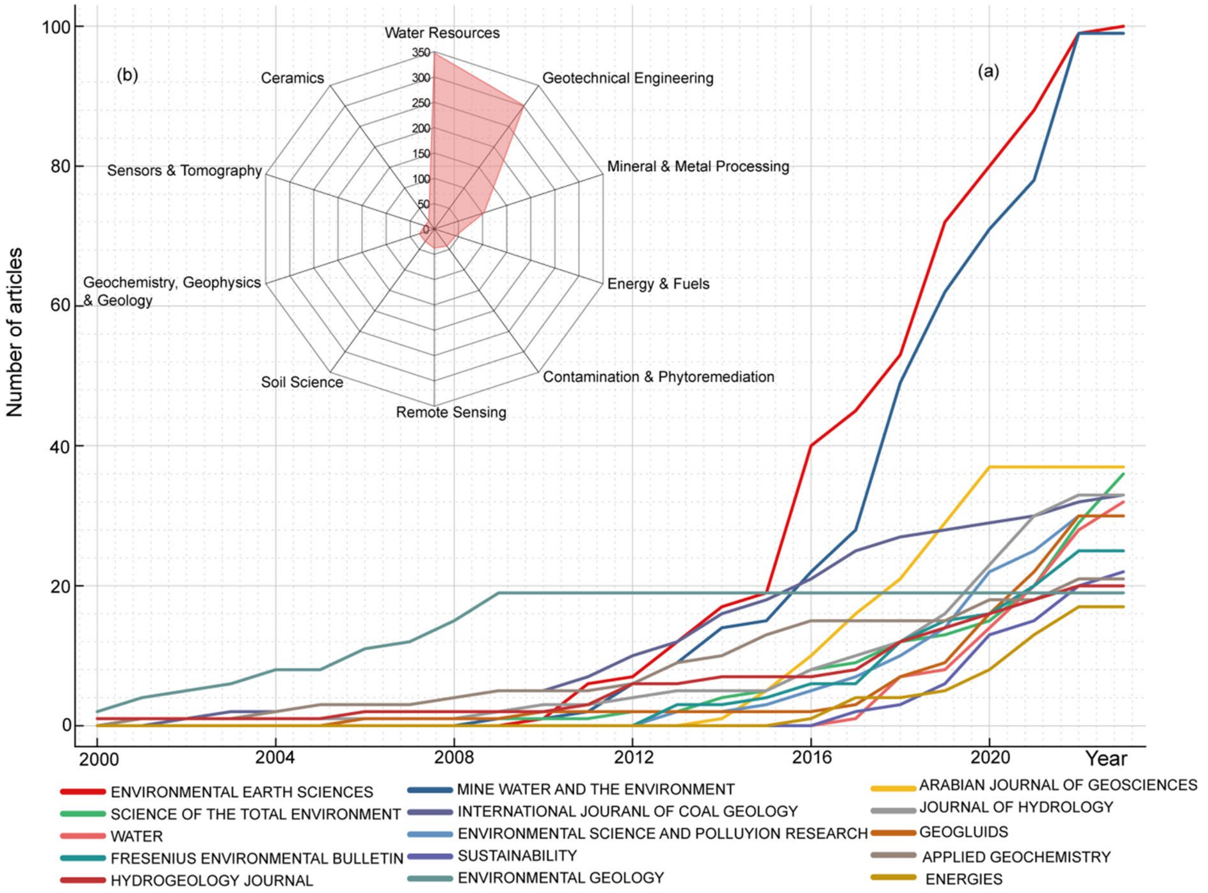


Fig. 4 The general trends of articles in the top 15 most productive journals (**a**) and the top 10 subjects related to coal mine groundwater research (**b**)

Table 2 The top 15 journals for coal mine groundwater research articles

Journal	h_index	NP	Average citations	IF (2021)
Environmental Earth Sciences	24	100	18.93	3.119
Mine Water and the Environment	21	99	14.41	2.688
Arabian Journal of Geosciences	14	37	12.95	1.827*
Science of the Total Environment	14	36	13.67	10.754
International Journal of Coal Geology	18	33	60.09	6.3
Journal of Hydrology	14	33	16.27	6.708
Water	8	32	6.97	3.53
Environmental Science and Pollution Research	12	30	15.13	5.19
Geofluids	6	30	4.53	2.006
Fresenius Environmental Bulletin	6	25	3.08	0.618
Sustainability	8	22	7.23	3.889
Applied Geochemistry	13	21	24.14	3.841
Hydrogeology Journal	12	20	20.30	3.151
Environmental Geology	14	19	36.58	1.127*

NP represents the number of published articles; Arabian Journal of Geosciences (IF:1.827*, 2020) and Environmental Geology (IF:1.127*, 2011)

3.3 Journal contribution and research topic

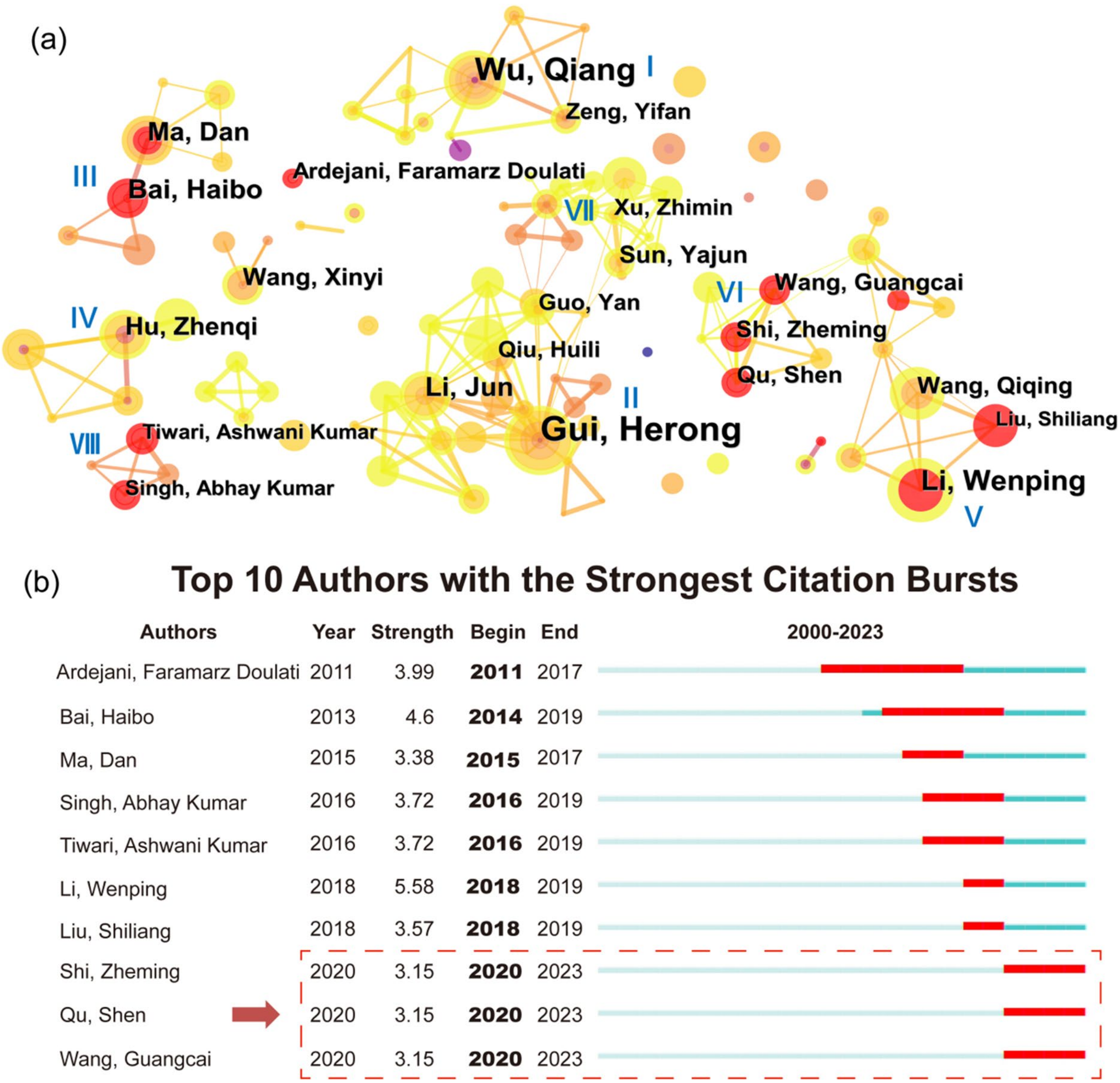
Figure 4a and Table 2 lists the top 15 journals (out of the 263 journals in the database). A total of 554 articles were included in 15 journals, representing 46.32% of the articles in the literature database. The top six journals, including Environmental Earth Science (100), Mine Water and the Environmental (99), Arabian Journal of Geosciences (37), Science of Total Environmental Science (36), International Journal of Coal Geology (33), and Journal of Hydrology (33), represented approximately 28.26% of all articles in the literature database. Although Environmental Earth Science, Mine Water and the Environment occupied the top two positions in terms of the number of articles, the average number of citations per article was relatively low, at 18.93 and 14.41, respectively. However, the International Journal of Coal Geology had the highest average number of citations per article (60.09), followed by Environmental Geology (36.58), Applied Geochemistry (24.14) and Hydrogeology Journal (20.30). The articles in these journals were mainly in the thematic areas of water resources, geotechnical engineering, mineral and metal processing, contamination, and phytoremediation. This indicates that these journals have contributed to the development of groundwater research in coal mining areas in a variety of research areas.

3.4 Author productivity

The g-index is an effective way to reflect the contributions of authors (or other aspects) to the field. A total of 470 authors participated in groundwater research on coal mines on a global scale in the database. Table 3 shows the top 15 authors in terms of the number of articles. We listed the g-index, h-index, average citations, and institutes. As can be seen, all come from China, reflecting the outstanding contribution of Chinese scholars to groundwater research related to coal mining. Gui Herong (37), Wu Qiang (28), Li Wenping (19), Bai Haibo (15), Li Jun (15), and Ma Dan (14) were the top six authors. Among them, Ma Dan is the scholar with the highest number of citations with an average of 57.5, followed by Wu Qiang (37.31), Bai Haibo (37.38), and Li Wenping (12.71), which reflects a great contribution to the development of groundwater research in coal mines. Figure 5a shows the key authors and co-authorships selected using the g-index algorithm. The key authors/co-author groups are mainly from China (I-VII) and India (VIII), and these research groups represent the mainstream directions of current groundwater research in the coal mining field, for example, the mechanism and risk assessment of mine-water outbursts (II, III, V, IV, VII), groundwater quality evaluation and environmental impact

Table 3 The top 10 authors for coal mine groundwater research

Rank	Author	Article numbers	h_index	g_index	Average citations
1	Gui Herong	37	11	15	6.84
2	Wu Qiang	28	18	29	29.87
3	Li Wenping	19	10	17	12.71
4	Bai Haibo	15	11	16	37.38
5	Li Jun	15	7	10	6.89
6	Ma Dan	14	14	16	57.5
7	Hu Zhenqi	13	7	13	13.29
8	Sun Yajun	12	6	12	11.85
9	Wang Xinyi	11	4	7	4.33
10	Wang Qiqing	10	5	11	15.27
11	Wang Guangcai	10	7	13	14.38
12	Qu Shen	10	5	9	8
13	Shi Zheming	10	5	9	7.42
14	Qiu Huili	9	5	8	8.67
15	Xu Zhimin	9	5	11	11.67



Authors	Year	Strength	Begin	End
Ardejani, Faramarz Doulati	2011	3.99	**2011**	2017
Bai, Haibo	2013	4.6	**2014**	2019
Ma, Dan	2015	3.38	**2015**	2017
Singh, Abhay Kumar	2016	3.72	**2016**	2019
Tiwari, Ashwani Kumar	2016	3.72	**2016**	2019
Li, Wenping	2018	5.58	**2018**	2019
Liu, Shiliang	2018	3.57	**2018**	2019
Shi, Zheming	2020	3.15	**2020**	2023
Qu, Shen	2020	3.15	**2020**	2023
Wang, Guangcai	2020	3.15	**2020**	2023

Fig. 5 Top cooperation network of authors (top 15) (**a**) and the top 10 authors with the strongest citation burst (**b**)

prediction (VIII), mine-water pollution management and resource utilization (I), and mining disturbance of aquifers and overburden hydraulic properties (VI). The research group represented by Gui Herong (#I) closely collaborates with other authors, followed by the research groups represented by Li, Wenping (#V) and Wang Guangcai (#VI). Furthermore, in terms of the top 10 burst authors from 2000 to 2023 (Fig. 5b), the research group represented by Wang Guangcai from the China University of Geosciences is more active in the field of groundwater research in mining areas, reflecting the trend of research on coal mining activities and hydrological processes.

3.5 Distribution of countries and institutions

The top 10 countries or regions and the top 15 institutions with the Top-N algorithm are listed in Tables 4 and 5, respectively. Chinese and American scholars have published most articles on groundwater research related to coal mining. As shown in Table 4, China contributed the most (60.12%) to

Table 4 Publications and cooperation among top 10 most productive country/regions

Rank	Country/region	Numbers	centrality	R (%)	h_index	Average article citations	SCP	MCP	MCP_Ratio
1	China	719	0.51	60.12	63	14.98	590	99	0.144
2	USA	134	0.38	11.20	42	29.63	66	18	0.214
3	Australia	70	0.1	5.85	25	17.48	34	16	0.32
4	India	63	0.12	5.27	27	20.36	55	6	0.098
5	Poland	54	0.07	4.52	17	11.78	45	4	0.082
6	Germany	40	0.39	3.34	17	14.58	13	13	0.5
7	England	36	0.15	3.01	21	23.83	25	5	0.167
8	South Africa	30	0.08	2.51	9	7.28	20	5	0.2
9	Canada	27	0.05	2.26	16	9.17	6	6	0.5
10	Spain	24	0.08	2.01	18	29.81	14	2	0.125

Single Country Publications (SCP) indicates that the authors of the article are from the same country. Multiple Country Publications (MCP) indicates that the authors of the article are from multiple countries, i.e. there is inter-country collaboration. MCP/Articles (MCP_Ratio): is the proportion of co-authored articles published in the country, a higher value indicates that the country has more co-authored articles with other countries. PR represents the percentage of numbers to the total number of published articles

Table 5 Top 10 most productive institutions

Rank	Institution	Numbers	Centrality	h_index	Average citations
1	China University of Mining and Technology	228	0.2	38	17.96
2	Anhui University Science and Technology	72	0.01	15	7.03
3	Suzhou University	55	0.01	12	6.28
4	China University of Geosciences	50	0.09	24	24.99
5	Henan Polytechnic University	49	0.02	12	7.9
6	Chinese Acad Sci	41	0.06	3	15.5
7	Shandong University Science and Technology	41	0	13	8.05
8	China University of Mining and Technology Beijing	38	0.02	13	13.56
9	Xian University Science and Technology	36	0.03	11	6.07
10	Hefei University of Technology	25	0	13	13.61
11	National engineering research centerCoal Mine Water Hazard Controll	22	0.01	8	8.09
12	Indian School of Mines	17	0	15	25.33
13	Central Mining Institute	16	0	9	14.68
14	Changan University	15	0	14	39.71
15	North China Institute of Science and Technology	15	0	6	8.93

groundwater research in coal mines with the highest h-index (63), followed by the USA (11.2%), Australia (5.85%), India (5.27%), and Poland (4.52%) in terms of publications. However, although researchers in China have published many articles, the average citations for the top four countries are Spain (29.81), the USA (29.63), England (23.83) and India (20.36), reflecting the influence of groundwater-related research in these countries. As shown in Table 5, the China University of Mining and Technology contributed the most (228) to the development of groundwater research in coal mines and had a high h-index (38). The China University of Geosciences and the Indian School of Mines have also contributed significantly to the development of groundwater in coal mines. They had high average citations per article of 24.99 and 25.33 respectively, and high h-indices of 24 and 15, respectively.

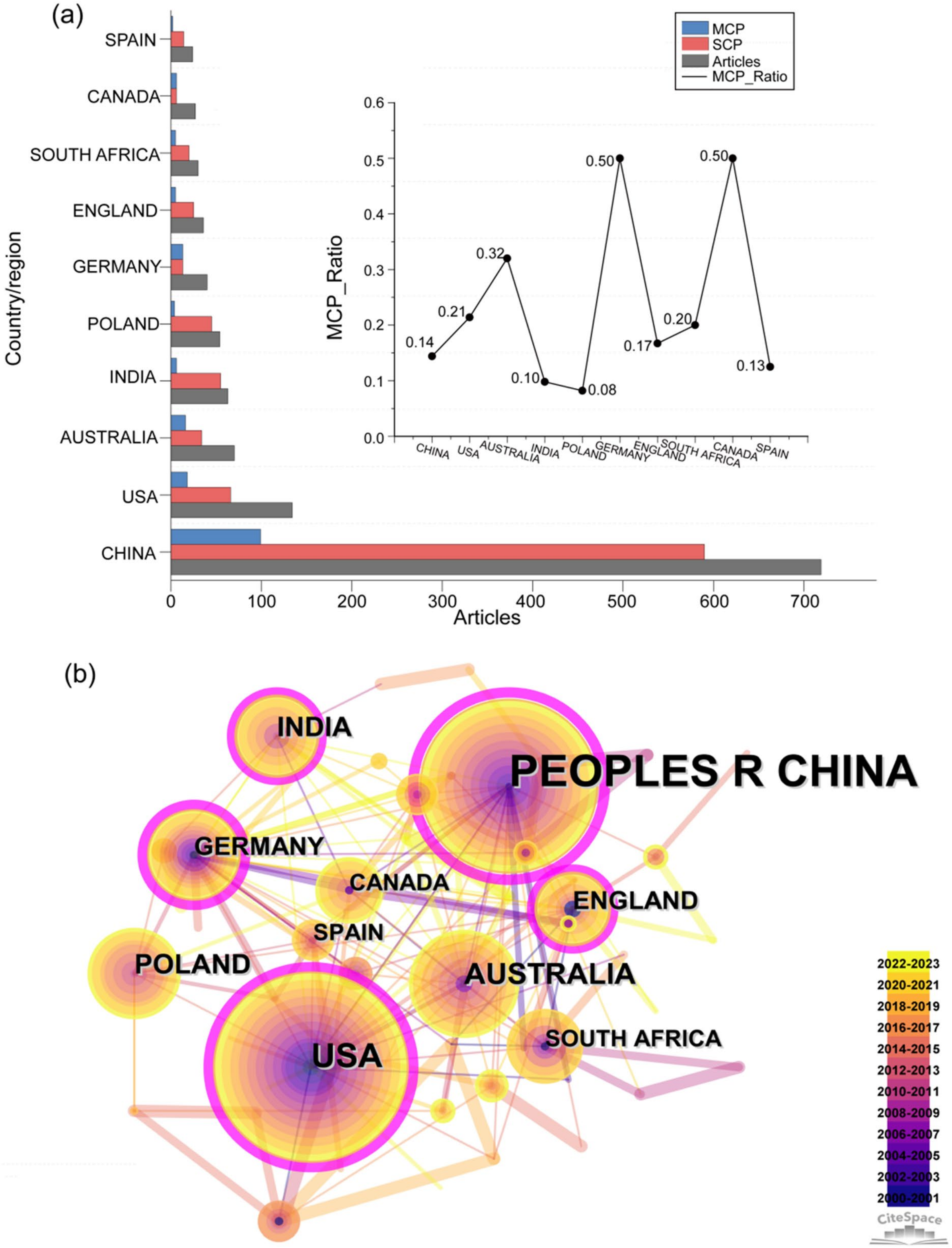
Changan University had a high average number of citations (39.71), which also reflects its great contributions to the development of this field.

The distribution and collaboration of the top 10 countries or regions and the top 15 institutions (Top-N% algorithm) are shown in Figs. 6 and 7. As shown in Fig. 6a, China (SCP:590), the USA (SCP:66), and India (SCP:55) published the most articles by local authors, whereas Australia, the USA, England, and China favored international collaboration due to their relatively high MCP_Ration (0.32, 0.21, 0.17, and 0.14, respectively). Furthermore, as shown in Fig. 6b, China, the USA, Australia, and Germany had larger nodes and represented the highest contributions to the field. England, the USA, South Africa, and Germany started earlier than the other countries/regions due to the darker central nodes. Furthermore, China, Germany, and the USA have high centralities of 0.51, 0.39, and 0.38, respectively, reflecting the contributions of these three countries to the promotion of research and cooperation. In contrast, although Poland, South Africa, Canada, and Spain also published many articles, their centrality was low (0.07, 0.08, 0.05, and 0.08, respectively), and the link between them was barely visible, indicating a lack of collaboration in these countries. As shown in Fig. 7, although Henan Polytechnic University of (7.9), Anhui University Science and Technology (7.03), and Suzhou University (6.28) published several articles in the field of coal mine groundwater research, their citations per article were lower than the average of the top 15 institutions (14.51). In contrast, the Indian School of Mines, Central Mining Institute, and Changan University had a high average number of citations per article (25.33, 14.68, and 39.71, respectively) despite publishing a few articles. Numerous international agencies such as WHO-PAHO (World Health Organization-Pan American Health Organization), IGRAC (International Groundwater Resources Assessment Center), IAH (International Association of Hydrology) and International Mine Water Association (IMWA), contributed greatly to the groundwater development in the coal mine. However, these institutions are not shown in Fig. 7, which may be related to the reading rules of CiteSpace, where institutions are not identified and are represented anonymously. In addition, to promote the sustainable development of groundwater research in mining areas, we strongly recommend that countries and institutional organizations actively engage in national cooperation.

3.6 Citations

Figure 8 shows the co-citation results for the top 15 authors selected by the Top-N algorithm (Fig. 8a) and the 12 clusters selected by the LLR algorithm (Fig. 8b). Some highly cited scholars have obtained widespread recognition in this field. The highly cited scientists and their representative publications are listed in Table 6. These publications involved fundamental concepts, laboratory experiments, numerical models, risk assessment, mine closure management, and groundwater resource protection and management, which can be considered the fundamental work of groundwater research in mining areas. Furthermore, we examined the affiliations of these scholars and found that they originated from the University (Younger PL) and Mining Research Agency (Liu J, Tiwary RK), which further represents the contribution of universities and research agencies to groundwater development in coal mining areas in terms of concepts, methodology, conservation policies, and revised guidelines.

As shown in Fig. 8b, the articles cited can be clustered into 12 groups that represent hot topics, issues, areas, or contents closely related to groundwater research in coal mines. In Fig. 8b, hydrogeochemical processes (#0) are an important part of mine hydrogeological investigations and mine-water hazard prevention and management. Therefore, the combination of hydro-chemical methods with environmental isotopes and other methods is widely used to study mine-water outbursts, underground drainage channels, hydraulic connectivity, slurry effects in different aquifers, regional water circulation, and water resource assessments (Meng and Maynard 2001; Wu et al. 2006; Gibbs 1970; Gui and Chen 2011; Singh et al. 2013; Wang et al. 2003). In contrast to traditional hydrogeochemical methods, the Random Forest (#4) is an artificial intelligence algorithm that has developed rapidly in recent years. It can efficiently handle large amounts of data and improve prediction accuracy. Furthermore, random forests have been widely used in groundwater quality assessment and prediction studies, such as groundwater contamination prediction (Tiwari et al. 2017) and coal mine and coal seam floor water burst risk assessment (Zhang et al. 2022), in which feature selection and variable importance assessment can be performed using less voluminous data. Hydrogeochemical methods and artificial


(a)
MCP
SCP
Articles
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Country/region
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SOUTH AFRICA
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SOUTH AFRICA
USA
2022-2023
2020-2021
2018-2019
2016-2017
2014-2015
2012-2013
2010-2011
2008-2009
2006-2007
2004-2005
2002-2003
2000-2001
CiteSpace

◂**Fig. 6** Articles and cooperation between countries or regions (top10). **a** number of publications and inter-country cooperation; **b** the cooperation network of the countries/regions

intelligence algorithms have become effective methods for quantifying water bursts (#7). It is well known that water burst is one of the common disasters that threaten coal mine safety production, and the water source and water channel are two factors of water burst. Therefore, the study of water channel formation and control method is the key to solve water burst disaster and prevention and control. Scholars have also explored the mechanism of water burst mechanism from numerical methods (Moya et al. 2014; Hamdi et al. 2018; Yin et al. 2018), experimental analysis (Booth 2007; Ma et al. 2015; Adhikary and Guo 2015), and engineering application. Miao et al. (2011) investigated the mechanism of water bursting and evaluated the risk of water bursting at the top and bottom of the coal seam. Furthermore, control factor analyses (#2) have been applied to hydrogeochemical processes and modeling (Cravotta 2008; Singh et al. 2013), hydro-chemical characteristics, spatial and temporal evolution mechanisms (Qian et al. 2017; Liu et al. 2020), coal mining impacts on groundwater systems and water resources (Zhang et al. 2022), and structural damage to aquifers and aquifer hydraulic connectivity because of mining disturbances (Li et al. 2015; Zhang 2005). These studies have addressed groundwater issues related to mining activities; for example, abandoned mines (#5) are mainly concerned with AMD or the transport of harmful contaminants from coal mine waste deposits (Younger 2000; Tiwary et al. 2001; Tiwari et al. 2017); and overburden aquifers (#5) and chalk aquifers (#8), where the rock mass is prone to deformation or damage because of mining activities (Miao et al. 2011). Overburden aquifers (#5) and chalk aquifers (#8) are areas where the rock is easily deformed or damaged by mining activities (Miao et al. 2011). Structural damage to an aquifer can lead to hydraulic connectivity of multiple aquifers, resulting in the risk of water bursting (Zhang et al. 2022; Li et al. 2016). The groundwater flow system (#6) is the control model for regional groundwater circulation and development and is a prerequisite for the analysis of the causes of water outbursts and their prevention (Mudd 2008; Zhang et al. 2022).

The risk of subsidence (#10) is an unavoidable geological and environmental hazard associated with coal mining and it is unavoidable (Hu et al. 2015;

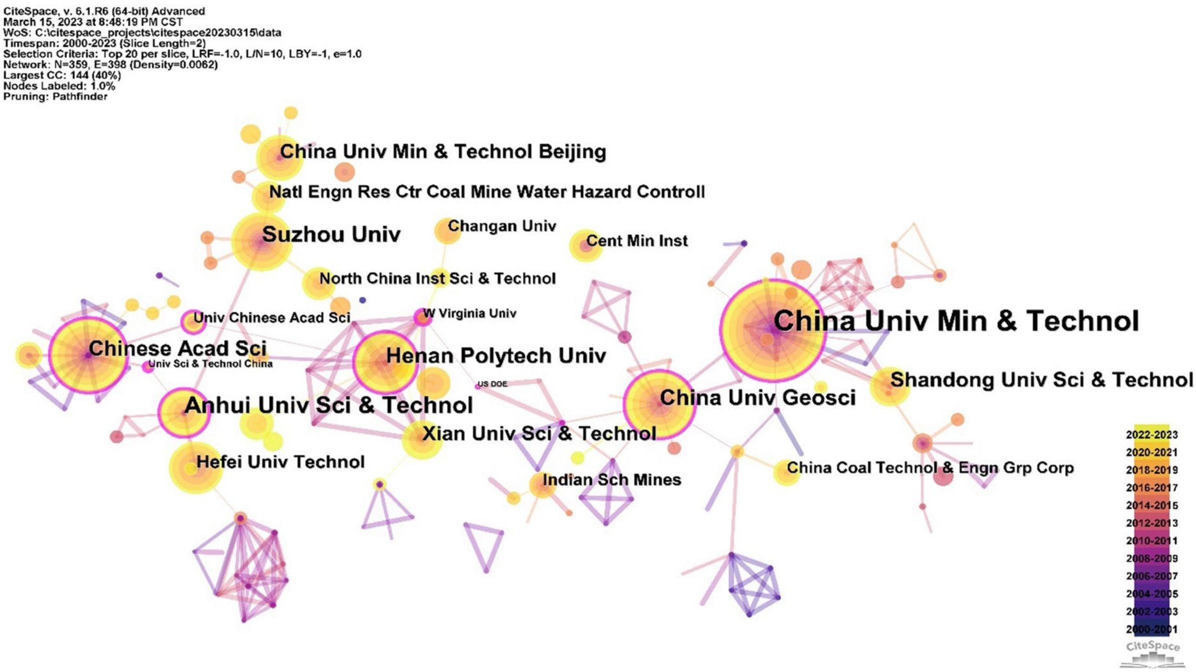

Fig. 7 The cooperation network of the institutions. (Top N algorithm)

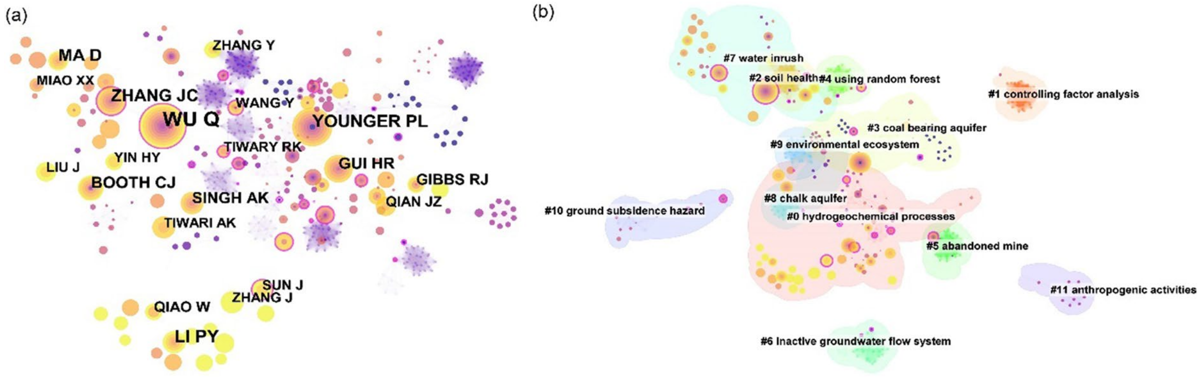

Fig. 8 Network map of co-citations analysis of coal mine groundwater research. **a** Top 15 authors (Top N algorithm); **b** Top 12 clusters (LLR clustering algorithm)

Table 6 Highly cited authors, citation times, and representative publications

Rank	Author	Count	Representative publications	Citation
1	WU Q	220	Management of karst water resources in mining area: dewatering in mines and demand for water supply in the Dongshan Mine of Taiyuan, Shanxi Province, North China	Wu et al. (2006)
2	LI PY	95	Preliminary assessment of hydraulic connectivity between river water and shallow groundwater and estimation of their transfer rate during dry season in the Shidi River, China	Li et al. (2016)
3	YOUNGER PL	88	Predicting temporal changes in total iron concentrations in groundwaters flowing from abandoned deep mines: a first approximation	Younger (2000)
4	ZHANG JC	79	Investigations of water inrushes from aquifers under coal seams	Zhang (2005)
5	MA D	76	Compaction and seepage properties of crushed limestone particle mixture: an experimental investigation for Ordovician karst collapse pillar groundwater inrush	Ma et al. (2015)
6	BOOTH CJ	63	Site-specific variation in the potentiometric response to subsidence above active longwall mining	Booth et al. (2000)
7	GUI HR	55	Hydrogeochemistric Evolution and Discrimination of Groundwater in Mining District	Gui and Chen (2011)
8	SINGH AK	51	Evaluation of hydrogeochemical processes and groundwater quality in the Jhansi district of Bundelkhand region, India	Singh et al. (2013)
9	GIBBS RJ	48	Mechanisms Controlling World Water Chemistry	Gibbs (1970)
10	QIAO W	41	Relevance Between Hydrochemical and Hydrodynamic Data in a Deep Karstified Limestone Aquifer: a Mining Area Case Study	Qiao et al. (2017)
11	WANG Y	35	Proterozoic anorogenic magmatic rocks and their constraints on mineralizations in the Bayan Obo deposit region	Wang et al. (2003)
12	QIAN JZ	34	Hydrochemical Characteristics and Groundwater Source Identification of a Multiple Aquifer System in a Coal Min	Qian et al. (2017)
13	LIU J	32	Hydrochemical characteristics and evolution processes of karst groundwater in Carboniferous Taiyuan formation in the Pingdingshan coalfield	Liu et al. (2020)
14	ZHANG J	32	Effects of multi-factors on the spatiotemporal variations of deep confined groundwater in coal mining regions, North China	Zhang et al. (2022)
15	TIWARY RK	31	Water, Air, and Soil Pollution	Tiwary (2001)

Booth 2006). Large-scale subsidence affects groundwater depth and soil use and requires multidisciplinary integration, such as GISs to predict the location of subsidence (Yin et al. 2018) and soil reclamation techniques to protect arable land resources (Hu et al. 2015). Human activities (#11), such as heavy water extraction for agricultural or industrial purposes, can affect the water supply to the surrounding area and thus damage groundwater resources (Tiwary et al. 2001). Karst and groundwater are not a single system because karst formations are a special type of landform that often forms important aquifers. However, it is accepted that karst aquifers are more vulnerable to climate change and human activity (Liu et al. 2020), and specialized research institutions assess groundwater in karst areas to understand karst hydrological processes and improve planning methods for sustainable development in karst areas (Wu et al. 2006; Sun et al. 2019a, b; Liu et al. 2020). The above studies were all concerned with environmental issues (#12) and ecosystems (#9) and aimed to reduce the impact of coal mining on groundwater resources, the geological environment, and ecosystems (Zhang et al. 2022; Cravotta et al. 2008; Younger 2000; Masood et al. 2020).

3.7 Keywords

A total of 526 keywords were included in the literature database with a total frequency of 3759. Table 7 summarizes the top 15 keywords by frequency. In the literature database, groundwater quality, AMD, and aquifers had the highest total frequency, and some water inrush in coal mine-related keywords (e.g., water balance, water inrush, fluid flow) and contamination-related keywords (e.g., heavy metals and trace elements) had a relatively high keyword frequency. Groundwater quality (6.7), heavy metal (5.59), AMD (5.13), aquifer (5.09), numerical simulation (5.05), water balance (4.91), contamination (4.83), fluid flow (4.52), water inrush (4.45), and subsidence (3.87) obtained a relatively high annual frequency in keywords, which represents their recent popularity combining the top 25 burst keywords with the total keyword list (Fig. 11), some recent keywords also obtained a relatively high annual frequency, including quality assessment (1.0), multivariate statistical analysis (1.0), risk assessment (1.91), health risk (1.8), water–rock interaction (1.67), deformation (5.33), drinking water (0.94), conceptual model (3.57), surface water (2.42), mine water (2.26). These high-frequency keywords also indicate the status of ground research in coal mines.

Figure 9a–d show the keyword co-occurrence analysis (Top-N algorithm) and the clustering analysis (LLR algorithm) for different periods (2000–2023 and 2018–2022). Figure 10 shows the results of the keyword clustering analysis with time slides using the Top-N and LLR algorithms. A comparison of Figs. 9 and 10 shows that groundwater quality, subsidence, and issues related to water inrush (water inrush, numerical simulation, aquifer, and source discrimination) and contamination (contamination, AMD, and heavy metals) always occurred at different times, both in terms of keyword co-occurrence analysis and clustering results. This suggests that most groundwater research in mining areas has been devoted to solving mine inrush problems (Wu and Wang 2006; Booth 2002, 2007; Evans et al. 2015). Hydrogeochemical (Singh et al. 2013; Zhang et al. 2022) and numerical modeling (Yin et al. 2018; Moya et al. 2014) are the primary methods used to minimize environmental and geological problems, such as groundwater contamination and subsidence because of mining activities (Tiwary 2001; Acharya and Kharel 2020; Hu et al. 2015).

Table 7 Keywords frequency, keyword annual frequency and start year in the literature database

No	Keywords	Keywords frequency	Start year	Annual frequency
1	Groundwater quality	154	2000	6.70
2	Acid mine drainage	118	2000	5.13
3	Aquifer	117	2000	5.09
4	Water balance	113	2000	4.91
5	Contamination	111	2000	4.83
6	Numerical simulation	101	2003	5.05
7	Water inrush	98	2001	4.45
8	Fluid flow	95	2002	4.52
9	Heavy metal	95	2006	5.59
10	Subsidence	89	2000	3.87
11	Conceptual model	82	2000	3.57
12	Impact	81	2001	3.68
13	Evolution	73	2000	3.17
14	Geochemistry	71	2000	3.09
15	Trace element	54	2001	2.45

Annual frequency = Keywords frequency/(2022 – start year)

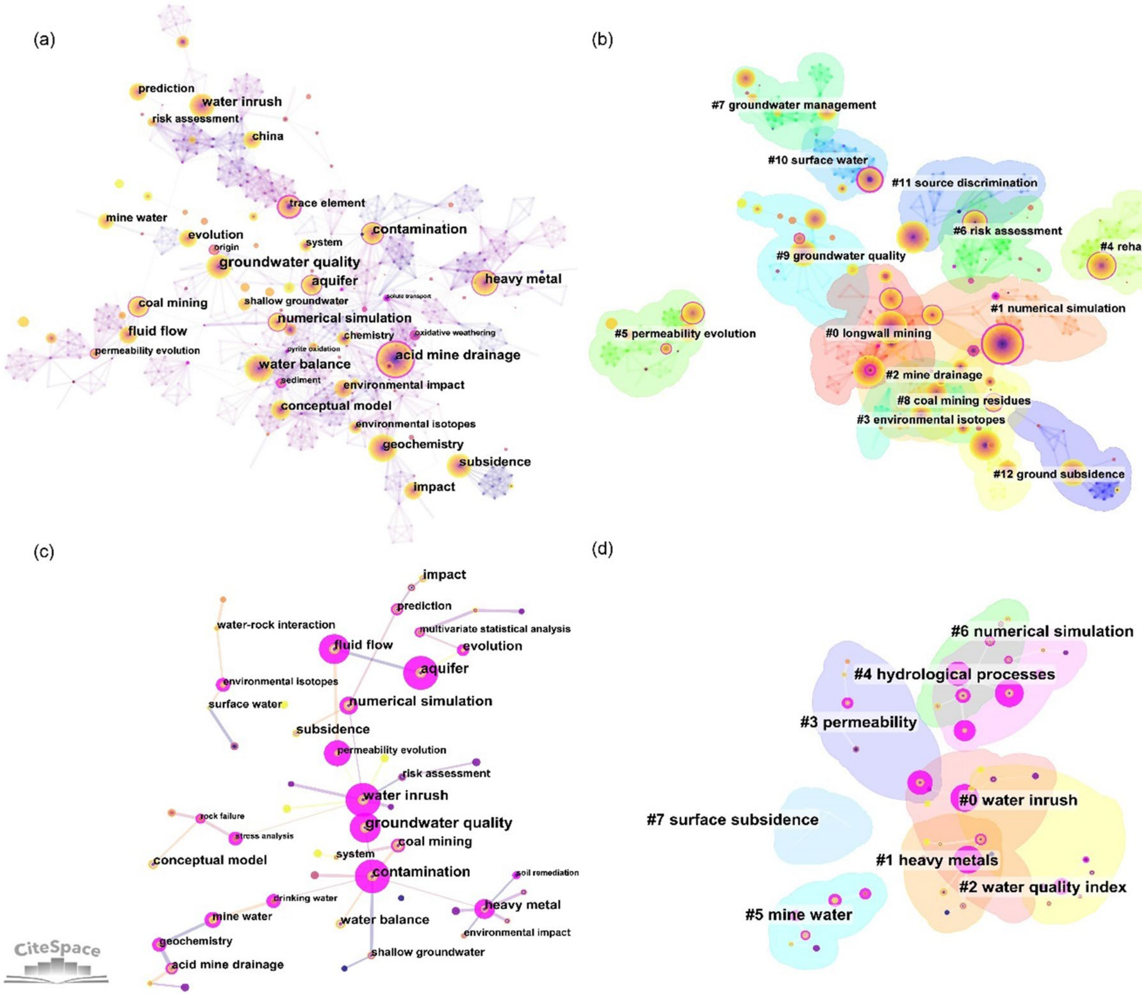

Fig. 9 Keyword analysis. **a** keyword co-occurrence analysis (2000–2023, top N algorithm); **b** keyword clustering analysis (2000–2023, LLR algorithm); **c** keyword co-occurrence analysis (2018–2022, top N algorithm); **d** keyword clustering analysis (2018–2022, LLR algorithm)

Besides the keywords commonly occurring above, the recent co-occurrence of keywords related to shallow groundwater and risk assessment (Fig. 9c) can be explained by the vulnerability of shallow groundwater to human activities (Chiew et al. 2018). Quantitatively analysis on the impact of human activities on groundwater systems and the geological environment is needed to conduct risk assessment and prediction studies related to groundwater and human health. This indicates that the impact of human activities on groundwater is a concern for groundwater studies in mining areas (Chabukdhara and Singh 2016). The numerical simulation, permeability evolution, groundwater quality, land subsidence, mine water, and water inrush were clustered into two periods (#1, #5, #9, #12, #13, and #14 in Fig. 9b, and #0, #2, #3, #5, #6, and #7 in Fig. 9d). These issues have been the focus of groundwater studies in coal mines. Figure 9b shows several other clusters related to mining methods (longwall mining), contaminant treatment (mine drainage and coal mining residues), mine-water outbursts, source identification techniques (environmental isotopes, source discrimination, fracture, and flow), risk assessment, groundwater management, surface water, and ecological restoration. This suggests that the overall goal of groundwater research in mining areas is not only to solve the problem of water outbursts and pollution in a local area, but also to

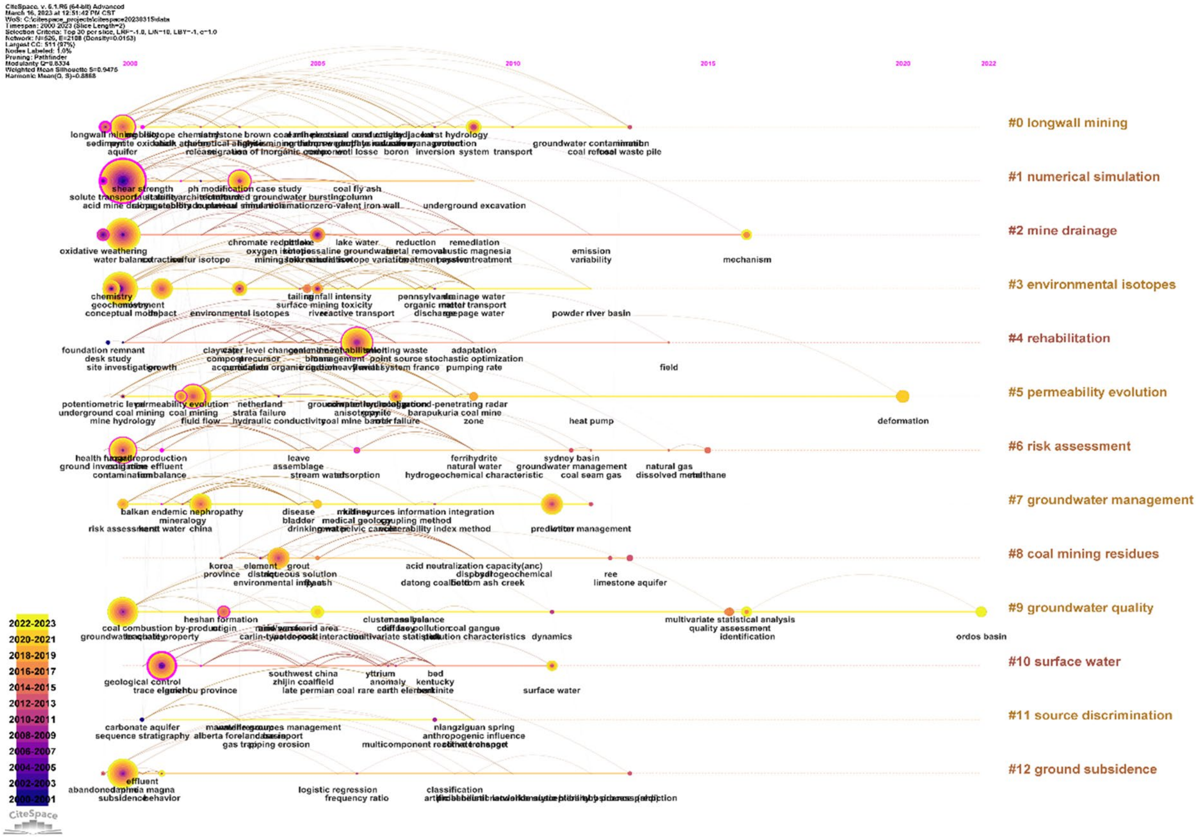

Fig. 10 Timeline visualization of co-occurring authors keywords network (2000–2023). (top N algorithm and LLR algorithm)

achieve the joint development of green coal mining, groundwater resource protection and management, and ecological environmental protection (Zeng et al. 2016; Wirth et al. 2018; Yang et al. 2022). Heavy metals (#1) and hydrological processes (#4) are two new clusters in Fig. 9d, indicating that research on the spatial and temporal evolution of hydrological processes between coal mining and groundwater is increasingly being conducted (Evans et al. 2015). This explores the dynamic evolution of the geological structure, groundwater environment, and ecological environment related to coal mining from a multidisciplinary perspective (State Administration of Work Safety 2010). Authors have also focused on the study of heavy metal pollution in relation to human health (Qu et al. 2022). This quantifies the impact of human activities (mining) on the groundwater environment to reduce the risk of groundwater pollution.

3.8 Research frontiers

3.8.1 Numerical modeling, conceptual modeling, and mechanisms

The study of the evolutionary patterns of hydrological processes in mining areas and the hazard mechanisms of aquifer structural damage are key scientific problems that must be urgently addressed to explore research related to coal resource mining and groundwater. In recent decades, many modeling approaches have been developed to quantify and predict the hydrogeological impacts of coal mining activities (Guo et al. 2012; Younger 2016; Hamdi et al. 2018; Malekzadeh et al. 2019; Moya et al. 2014). As shown in Table 7, numerical simulations and conceptual modeling studies have been the dominant and mainstream approaches to groundwater studies in mining

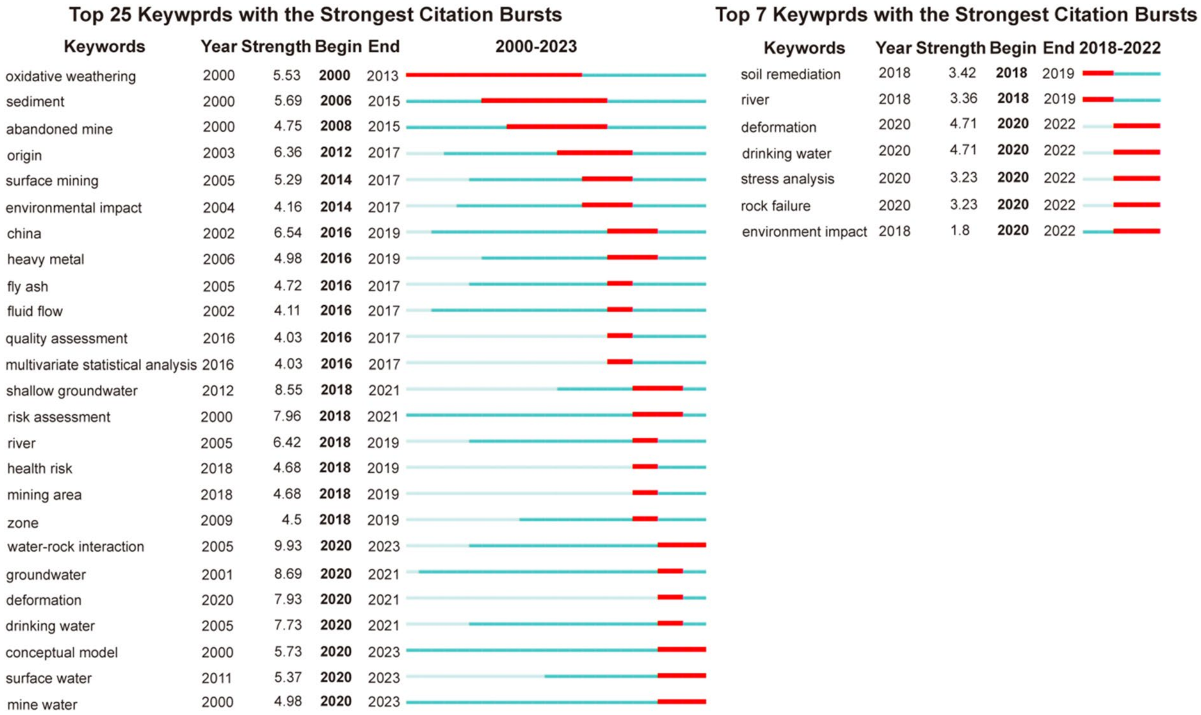

Fig. 11 The keywords with the strongest citation bursts. **a** top 25 keywords (2000–2023) and **b** top 7 keywords (2000–2023). The red area represents the duration of keyword mutation

areas over the last few decades. These appear in two clusters (#1 in Fig. 9b and #6 in Fig. 9d). In recent years, deformation, rock failure, and stress analyses (Fig. 11) have emerged as keywords of interest along with new clusters of permeability (#3) and hydrological processes (#4) (Fig. 9d). This indicates that the study of rock deformation and fractures caused by mining activities, and the mechanisms of their evolution in relation to aquifer permeability, remains challenging and frontier research. Therefore, it is important to understand the mechanisms of mining overburden fractures (Sun et al. 2019a, b) and the groundwater flow transport patterns under mining disturbances (Li et al. 2015). This provides a scientific basis for the control of mining rock formation, groundwater transport, optimal mining design, and ecological protection of mining areas (Booth et al. 2000). For decades, researchers have combined geological structures with groundwater movements associated with mining processes to construct physical models from which numerical simulations can be performed. This has become an effective method to analyze the mechanisms of rock deformation and sudden water flow caused by coal mining (Li et al. 2016; Wu et al. 2006; Booth 2007; Ma et al. 2015; Zhang 2005). Zhang (2005) proposed four factors that control sudden flow: stratigraphic pressure, mine size, geological structure, and water pressure of the underlying aquifer. Furthermore, some scholars have made advances in basic theories, such as rock and water stress relationships, strong percolation, major stratification, and disasters (Zhao et al. 2014; Zhu et al. 2017, 2020; Sun et al. 2019a, b). Therefore, based on theoretical analysis and numerical simulation results, combined with the requirements of actual engineering, the study of the deformation characteristics of mining overburden and the mechanism of groundwater flow movement is important in revealing disaster-causing mechanisms and improving the level of water damage prevention and control in mines.

3.8.2 Feedback mechanisms between anthropogenic-environmental and aquifer systems

"Scientific Mining" and "Green Mining" both emphasize that coal resources should be extracted in a way that protects water resources and restores the ecological environment (Wu et al. 2006). Many of the important keywords and clustering results can be explained by the interrelationships between human activities and environmental and groundwater systems, as well as the inherent feedback between systems (Dearing et al. 2014; Booth 2006; Tiwary 2001). These include groundwater contamination (AMD, heavy metals, contamination, trace elements, and coal mining residues), mine-water treatment (mine water and rehabilitation), and environmental issues (environmental isotopes and impacts). Soil remediation and environmental impacts have also appeared among the emerging keywords in recent years (Fig. 11), indicating that human activities have affected the groundwater flow system and ecological balance in mining areas, such as mine drainage, coal mine waste accumulation, open-pit backfilling, tailings, and coal wash disposal with dissolved organic matter, petroleum species, and trace and heavy metals, which have the potential to contaminate groundwater and cause a range of serious environmental impacts on the surrounding soil, surface groundwater, and surface water (Bell et al. 2006; Younger et al. 2002; Adam and Paul 2000). AMD (Akcil and Koldas 2006) and land use (Guo et al. 2019) are the two most prominent issues. AMD contaminates catchments with high heavy metal concentrations and acidic water, creating a toxic environment that negatively affects aquatic ecosystems (Akcil and Koldas 2006; Bell et al. 2006; Cravotta 2015) and human health (Qu et al. 2022). There are no specific regulations for the discharge of mine drainage and no water quality targets. Furthermore, due to the lack of data, understanding of mine water in different regions is limited. Addressing groundwater contamination is imperative for modern society (Adam and Paul 2000; Bester and Vermeulen 2010; Jordan 2009). During the past few decades, researchers have explored groundwater remediation techniques that combine remote sensing and biogeochemistry for biogenic treatment to address the sources of AMD problems (Acharya and Kharel 2020). Land use is an important environmental indicator of ecological change and is an expression of the results of human activities and the use of natural resources. Therefore, it has become a critical factor in integrated environmental and economic analyses (Zipper and Skousen 2021; Martins et al. 2022). In the future, it will be necessary to develop subsidence plans to maximize the use of arable land, ensure food security, and maintain regional ecosystem stability. This is the only way to achieve sustainable use of ecological resources and integrate economic, social, and environmental benefits.

3.8.3 Ground subsidence management

Ground subsidence in keyword co-occurrence and cluster analyses has interested researchers, indicating its importance in the study of groundwater in mining areas (Ghabraie et al. 2015; McCay et al. 2018). Subsidence is an environmental geological hazard in which the regional elevation of the ground decreases under the influence of natural factors or human activities (Seyoum et al. 2015). Ground subsidence is now a global problem as it can trigger secondary disasters, such as ground rupture and loss of groundwater resources (Zhu et al. 2017). Coal resource mining is one of the main causes of ground subsidence (Suchowerska et al. 2016), and remote sensing (e.g., InSAR), long-term monitoring of surface deformation (Vervoort and Declercq 2017), numerical simulations, and theoretical analyses (Sepehri et al. 2017) are widely used to predict subsidence in mining areas. Remote sensing, such as InSAR, and numerical simulation methods, are effective for analyzing the effects of groundwater mining on surface subsidence (Ghabraie et al. 2015). However, continued attention should be paid to research on the formation mechanisms of mining subsidence and its effects on groundwater systems, as surface movement deformation caused by underground mining and its effects on groundwater resources are complex processes.

3.8.4 *Groundwater quality evaluation and risk assessment*

Groundwater quality evaluation and risk assessment were two important keywords, with annual keyword frequencies of 6.70 and 1.91, respectively. As shown in Table 7, the keyword co-occurrence frequency of groundwater quality was first for the last 20 years (2000–2023) and within the last 5 years (2018–2022), as well as clusters for both periods (#9 in Fig. 9b and #2 in Fig. 9d). Risk assessment has become more frequent in keyword co-occurrence analyses over the last five years (Fig. 9c). In recent years, risk assessment and health risks have emerged as keywords (Fig. 11). This indicates that monitoring groundwater quality, identifying water sources, and assessing changes in water quality and risks associated with mine outbursts are important tasks in drinking water and groundwater protection studies in mines, due to their potential impacts on human health and the natural environment (Younger 2000; Zhang et al. 2016, 2022; Qian et al. 2017; Sahoo and Somnath 2020; Qu et al. 2021). It is also a research frontier that deserves public attention and remains a complex and challenging problem. In recent decades, many scientific tools and methods have been widely used to assess water quality and evaluate and predict abrupt water hazards. These include traditional hydro-geochemistry methods, multiple distance statistical analysis, vulnerability index method, gray relationship analysis evaluation system, coupled GIS and artificial neural network models, fuzzy integrated evaluation system, variable weight models, random forest, and self-organizing graph algorithms (Mondal et al. 2013; Yin et al. 2018; Qu et al. 2022; Afonso et al. 2019; Malekzadeh et al. 2019). However, various mathematical methods or artificial intelligence algorithms have limitations in practical engineering applications. However, based on a full understanding of mine water filling conditions and combined with specific engineering practices, more desirable results can also be obtained. Therefore, the establishment of a systematic evaluation system for groundwater quality and sudden water hazards in coal mines is important to improve the theory of coal mine-water damage prevention and control and helps decision makers to better manage groundwater resources in mines. Therefore, establishing a systematic evaluation system for groundwater quality and abrupt water hazards in coal mines is important to improve the theory of preventing and controlling water damage in coal mines and helps decision makers to better manage groundwater resources in mines.

3.8.5 *Management of coal mine groundwater resources*

Groundwater and surface water are integral water resources and are essential factors in groundwater hydrology research. Groundwater and surface water are integral water resources and are the most important factors in groundwater hydrology research. Furthermore, sustainable groundwater management is inherently linked to systems related to agricultural production, drinking water supply, and environmental issues, including climate change (Jiang et al. 2015). Therefore, the ultimate of groundwater research is to conserve and manage groundwater resources in mining areas. Groundwater management (#7) and surface water (#10) appeared in the keyword clusters. Shallow groundwater (Table 7) appeared more frequently in recent keyword co-occurrences and hydrological processes (#4) became a new cluster (Fig. 9d). Furthermore, surface water-related terms, such as river, drinking water, and surface water (Fig. 11), have appeared in recent years. This represents a gradual shift in groundwater management in mining areas to a combined groundwater and surface water management model. In the coming years, this will become an important issue for groundwater research in mining areas. Sustainable groundwater management is inextricably related to agricultural production, drinking water supply systems, and broader environmental issues, including climate change (Todd et al. 2019; Wu and Wang 2006; Zhang et al. 2016).

3.9 Challenges, prospects, and suggestions

3.9.1 *Challenges*

The damage to groundwater resources from coal mining is a major issue that must be addressed to achieve green coal development and ecological construction in mining areas (Zeng et al. 2016). During safe coal mining, water is extracted from the upper and lower aquifers. This causes groundwater loss and affects shallow surface ecology (Masood et al. 2020). In addition, the entire coal life cycle from mining to pit closure will pollute and damage the mine groundwater environment, especially after pit closure when the pit accumulates water, the temperature, pressure, and redox environment in the pit change, and the complex water–rock interaction between water and coal rock and water and mining waste occurs together, polluting groundwater (Cravotta 2008; Welch et al. 2021). These effluents seriously contaminate the regional groundwater environment by infiltrating aquifers through pathways such as mining-induced fractures, fault-associated fractures, and poorly sealed boreholes (Younger et al. 2002). Therefore, mine water is an important resource for this purpose. Using mine-water resources is important for the protection and use of groundwater in mining areas. If the construction of a groundwater resource bank can be included in the mine development plan, mine drainage, pit water, and mine water can be reused as resources (Younger 2016; Jason et al. 2016) or used as a source of heat recovery/disposed water in a low carbon heating system (Banks et al. 2017; Peralta et al. 2015; Todd et al. 2019).

3.10 Prospects and suggestions

Although there are certain groundwater and geological environmental problems in coal mining areas, due to the differences in the hydrogeological structures and background of different mining areas, the degree of environmental impact varies, both negative and positive environmental and ecological impacts, and needs to be scientifically differentiated and quantitatively studied.

Research on coal mining and groundwater can be summarized into two aspects. First, the impact of coal mining on the dynamic groundwater environment and the chemical groundwater environment, the former being mainly the disturbance of overburden and aquifers by mining, and the latter being related to groundwater pollution; second, the impact of the change in the groundwater flow system on coal production, such as the loss of life and property caused by an abrupt water rise in coal mines. Therefore, it is a key scientific issue in the study of groundwater in mines to explore the development law of the overburden fracture zone of coal mining and the groundwater transport mechanism and to master the law of groundwater quality change under the water–rock coupling action in groundwater transport and storage. This is also the theoretical basis for the use of water resources in mines. It is also necessary to focus on the development of precise detection instruments and equipment to achieve accurate exploration and prediction of mine hydrogeological information, such as mine-water source, water quantity, and water path, and to study the precise detection technology of the overburden structure and aquifer characteristics of coal mining under complex hydrogeological conditions, which is also the direction of future necessary efforts. Many follow-up efforts have been made, including, but not limited to, detailed hydrological investigations, rational land planning, reasonable and equitable allocation and use of water resources, water pollution control and monitoring, and health risk assessment for the protection, use, and management of groundwater resources in mining areas. International cooperation must be strengthened to integrate green mining with the goal of sustainable development of groundwater resources because there are significant gaps in research on the protection, use, and management of groundwater resources in coal mining areas worldwide.

4 Limitations

This study uses accepted bibliometric analysis methods. However, scientometric analyses have limitations. These can be summarized as follows. (1) The search was limited to the WoS core collection database to build a research database for citation analysis, excluding other databases such as PubMed, Scopus, and Google Scholar, making it extremely difficult to consider all relevant publications worldwide. This is a common limitation of bibliometric analysis. (2) Selecting "article" as the only publication type is a relatively effective way to exclude low quality publications from bibliometric analysis. However, it may ignore important publications, such as notes, letters, project reports, conference proceedings, and dissertations that are compatible with bibliometric software. These publications are not compatible with bibliometric software, and manual library construction cannot guarantee publication quality. (3) Bias in citation-related indicators, where the cited literature or the authors depend on the results of a particular study, may lead to an under use of the available evidence; other aspects include self-citation, authorship, or the impact factor of journals. (4) Ambiguity in the identification of keywords can also affect the results of bibliometric analysis. In this study, manual clean-up was performed to ensure that duplicate entries were correctly combined. However, it was impossible to ensure that all entries were checked. Despite these limitations, this study provided a comprehensive view of groundwater research in coal mines on a global scale.

5 Conclusion

Groundwater is an important resource; however, in many parts of the world, groundwater-related problems caused by coal mining have raised environmental, geological, and ecological concerns. With improvements in technology in the coal industry, groundwater research in mining areas has flourished, and it is necessary to understand its past research base, future trends, and research hotspots. Therefore, 1196 articles related to coal mining and groundwater were extracted from the WoSCC database for analysis. By visualizing trends in publications, related disciplines, journals, author productivity, countries or regions, institutions, citations, and keywords, trends in groundwater research related to coal mining were analyzed from a global perspective. The impact of coal mining on groundwater resources is receiving increasing attention worldwide. A significant increase in the number of articles, citations, interdisciplinary studies, and new keywords has led to the development of global research on mining activities and groundwater in coal mining areas. Research on coal mining and groundwater involves several disciplines. These fields include mining and safety, environmental science, water resources, geochemistry, and geophysics. Many countries have contributed to groundwater research in mining areas, with developed countries such as the United States continuing to lead historically; however, research results from developing countries, including China and India, are also increasing significantly. There are still urgent problems and challenges to be solved, such as safe mining of coal resources, protection and use of groundwater resources, groundwater pollution, and geological and ecological environmental problems caused by the mining process. We propose that the goals of "Green Mining" and "Sustainable Management of Groundwater Resources" are closely linked and that working together, countries around the world and international organizations and institutions can make a real difference in achieving this goal.

Author contribution YX: Data curation, Writing—original draft, Conceptualization, Methodology. SP: Funding acquisition, Writing—review and editing, Supervision. WD: Investigation, Resources.

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Data availability Data will be made available on request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical approval Not applicable, Ethics approval was not required for this research.

Consent for publication All authors agreed to publish.

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