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REVIEW

A Scientometric Analysis of Trends in Coal Mine Water Inrush Prevention and Control for the Period 2000–2019

Shuning Dong[1,2] · Liwei Zheng[1] · Shengli Tang[1] · Pingzhou Shi[3]

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Abstract

Water inrush hazards in coal mines pose a great risk to the safety of miners and coal production. We studied journal articles on coal mine water inrush prevention and control from 2000 to March 2019 using data from the Web of Science Core Collection V.5.32 database. We used CiteSpace V.5.3.R11 software to analyse the literature, including countries, institutions, authors, disciplines, journals, hot topics, and research frontiers. A total of 1612 published papers on coal mine water inrush prevention and control research were identified. China and the USA had the highest numbers of publications in this field. The China University of Mining and Technology was the most influential research institution. The journal with the largest number of relevant publications was the International Journal of Coal Geology. Hidden water disasters, quantitative evaluation of aquicludes, and rapid identification of water inrush sources are still unresolved problems. Improvement of electromagnetic methods, intelligent mine water monitoring, and three-dimensional hydrogeological systems were the leading research trends in this field.

Keywords Coal mine safety · Bibliometric analysis · CiteSpace · WoSCC

Introduction

Coal is the fossil fuel with the largest global reserves. It is a major electric-power energy source in most countries and an important component of global energy resources (Chen et al. 2014a, b). Global coal consumption in 2017 was equivalent to 3.75 billion tonnes of oil, and coal is likely to remain an important growth enabler and energy source for decades to come (World Coal Association 2018). However, coal mining is a hazardous process, with water hazards in particular seriously threatening worker safety and causing huge losses to the industry in China (Wu et al. 2013a, b). Furthermore, if the mine water inrush channel is connected to the main aquifer system, it can affect groundwater levels, disrupt the local water system equilibrium, and damage the ecological environment, with excessive water inrush leading to instability of overlying strata and local collapse (Sun et al. 2016; Wu et al. 2009). The prevention and control of coal-mine water hazards are therefore important in protecting lives, reducing losses, and ensuring smooth mine operation. To these ends, there have been many studies of risk assessment and water inrush prediction (Duan et al. 2012; Li et al. 2017; Meng et al. 2012). Risk assessment methods can be improved using geographic information system (GIS) Bayesian networks (Dong et al. 2012), the vulnerability index method (Wu et al. 2011), principal-component logistic regression models (Liu et al. 2018a, b), rock-breaking theory, water pressure transmission theory (He et al. 2018), fuzzy-logic Delphi analytical hierarchy processes, and grey correlation analyses (Qiu et al. 2017). A scientific analysis of coal-mine water discharge requires qualitative and quantitative study of water inrush in coal aquifers (Wu et al. 2015a, b, 2017; Wu and Zhou 2008; Xu et al. 2018; Zhang et al. 2017). Methods of rapidly identifying water inrush sources have been studied (Chen et al. 2017; Dong et al.

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✉ Liwei Zheng
357766215@qq.com

[1] College of Geology and Environment, Xi'an University of Science and Technology, Xi'an 710054, China

[2] Xi'an Research Institute of China Coal Technology and Engineering Group Corp, Xi'an 710054, China

[3] Southwest Petroleum University, Chengdu 610500, China

2018; Gui et al. 2018; Lu et al. 2018; Wu et al. 2013a, b), as this is important in preventing and controlling water inrush. Numerical simulations have improved theoretical studies of coal-mine water hazards and have promoted the study of water inrush mechanisms and related problems in coal mines (Light and Donovan 2015; Lu and Wang 2015; Meng et al. 2018; Qi et al. 2017; Yang et al. 2014; Yin et al. 2016). Geophysical research plays an important role in the detection and control of coal-mine water hazards, especially with respect to invisible water hazards (Yang et al. 2017).

Academic journals have published a large number of papers on coal mine water inrush prevention and control research since the past two decades. However, there has not previously been a review mapping linkages and working relationships between researchers in this field, or an analyses of co-citation clusters, keywords, or research clusters. We used CiteSpace V.5.3.R11 software to conduct a visual scientometrics analysis. The advantage of CiteSpace is that it enables investigation of specific research areas through analysis of citations, co-citations, and geographical distributions (García-Lillo et al. 2016; Yu and Shi 2015). CiteSpace has been widely used in detecting research trends, author cooperation analysis, journal development, and subject field development (Merigó and Yang 2017; Wang and Xu 2016).

The purpose of this study was to comprehensively and systematically review research on water-disaster prevention in coal mines, with our analysis focusing mainly on the network of cooperation among countries, co-authorship, and co-occurring keywords identified by CiteSpace. Knowledge domains, research patterns, intellectual structures, and emerging trends in this field were explored to provide accurate and comprehensive information on research topics and trends over time from different perspectives.

Data Acquisition and Methods

Data Collection and Processing

The paper retrieval source was the Web of Science Core Collection (WoSCC) V.5.32: Science Citation Index Expanded (SCI-E), Social Sciences Citation Index (SSCI), and Science Citation Index Expanded (CCR-Expanded), maintained by Clarivate Analytics (Chen et al. 2014a, b). The search terms included TS (Topic Search) = [(coal and mine and water) not (environmental or ash or acid or metal)]. This database constitutes the most comprehensive and frequently used scientific database in most fields. Records including titles, abstracts, and cited references were exported to CiteSpace for analysis based on the frequency of studies of coal-mine water-hazard prevention and control from January 2000 to March 2019 (the research period for this entire study). A total of 1612 journal articles were downloaded and recorded, with search details being summarized in supplemental Table S-1.

Total publications (TP) of all types in the SCI-E database increased from 25 in 2000 to 296 in 2018 (Fig. 1). A total of 1612 publications related to water-disaster prevention in coal mines were identified for the research period and were categorized into 11 document types: article, proceedings paper, review, book chapter, editorial material, meeting abstract, reprint, biographical item, early access, letter, and news item. Articles were the dominant document publication type at 99% of the total.

Methods of Scientometric Analysis

CiteSpace is a Java-based scientific visualization software package used for analysing and visualizing co-citation networks, developed by Chen (2006). The software provides functions for facilitating understanding and interpretation of network patterns, including identification of major topic areas and 'hotspots', and automatically labelling clusters. Contributing authors, countries, and journals were mapped to aid identification and visualization of the major contributing factors in the development of the coal-mine water inrush knowledge map. 'Hot' research topics and frontline research in water-disaster prevention in coal mines were identified based on the frequency of popular key words. In viewing the maps, a node represents one item, such as a keyword, journal, or reference, and the links describe the co-citation or co-occurrence between nodes (Xie 2015). Furthermore, each node is depicted with a series of rings of different colour, where blue indicates the oldest and orange the latest data. CiteSpace also makes it easier to identify pivotal points by recognizing nodes with high betweenness centrality (Freeman 2008). Pivotal points are highlighted with a purple ring in visualized networks.

For this study, basic parameter settings included pruning, time slicing, and linking. We employed Minimum Spanning Tree (MST), a network pruning algorithm supported by CiteSpace, because it is relatively simple to use. The cosine function was used to handle strengths between cluster links and nodes, with the range type set as 'within slices'. As detailed in the following sections, a number of options were chosen to analyse parameters based on centrality and to investigate frequencies and networks.

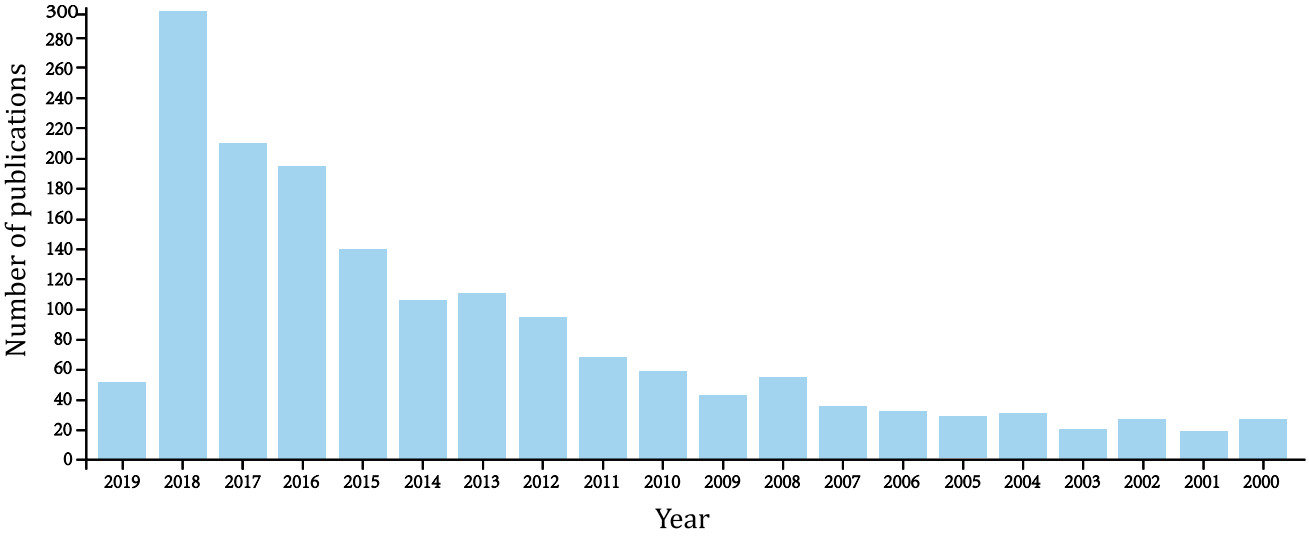

Fig. 1 Publication output performance in coal mine water inrush prevention and control during January 2000 to March 2019

Results and Discussion

Country and Institution Analysis

From January 2000 to March 2019, 29 nodes and 59 links in partner countries formed a network, as shown in Fig. 2, in which the different time zones are depicted by different colours, country significance is indicated by circle size (the more articles published, the bigger the circle), and lines between nodes represent collaboration links with strengths proportional to line thickness. Ten countries dominate, with China having published the most papers (Supplemental Table S-2). China is the world's largest coal producer and consumer; China's coal output in 2018 exceeded 3.5 billion tonnes, accounting for 45% of the total global coal output. China also has, by far, the greatest frequency of water inrush disasters (Li 2018). China's number of publications on the topic is followed by 274 articles from the USA.

Publications from 163 research institutes were extracted (Fig. 3), mainly from China, the USA, Poland, Australia, the UK, and Canada. In China, the China University of Mining and Technology, Shandong University of Science and Technology, Chinese Academy of Sciences, Henan Polytechnic University, Anhui Science and Technology University, Chongqing universities, China University of Geosciences, Taiyuan University of Technology, Soochow University, and the Xi'an University of Science and Technology were the major institutes. In the USA, the most productive institutes were the University of Kentucky (14 articles), Pennsylvania State University (13 articles), West Virginia University (13 articles), Virginia Tech (12 articles), University of Arizona

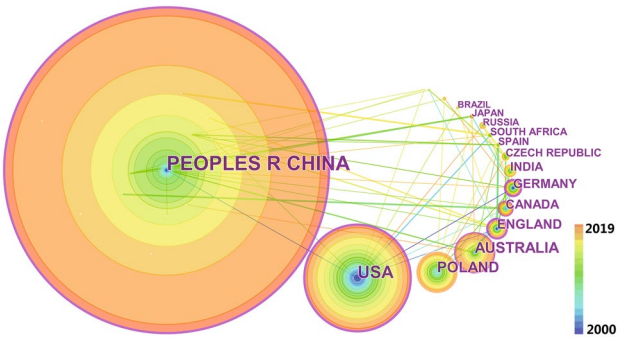

Fig. 2 The cooperation network of the productive countries in coal mine water inrush prevention and control during 2000–2019

(6 articles), and Duke University (6 articles). In Poland, the most productive institutions are Silesian University (12 articles) and the Silesian University of Technology (9 articles); in Australia are the University of Queensland (19 articles), Monash University (8 articles), and University of Wollongong (4 articles); and in the UK and Canada are the University of Newcastle (10 articles), and the University of British Columbia (7 articles). Figure 3 illustrates cooperation between institutions within countries; the cooperation between the China University of Mining and Technology and other institutions is the most extensive.

The top 10 most productive institutions are listed in supplemental Table S-3. First-ranked China University of Mining and Technology published 348 articles, and second-ranked Shandong University of Science and Technology

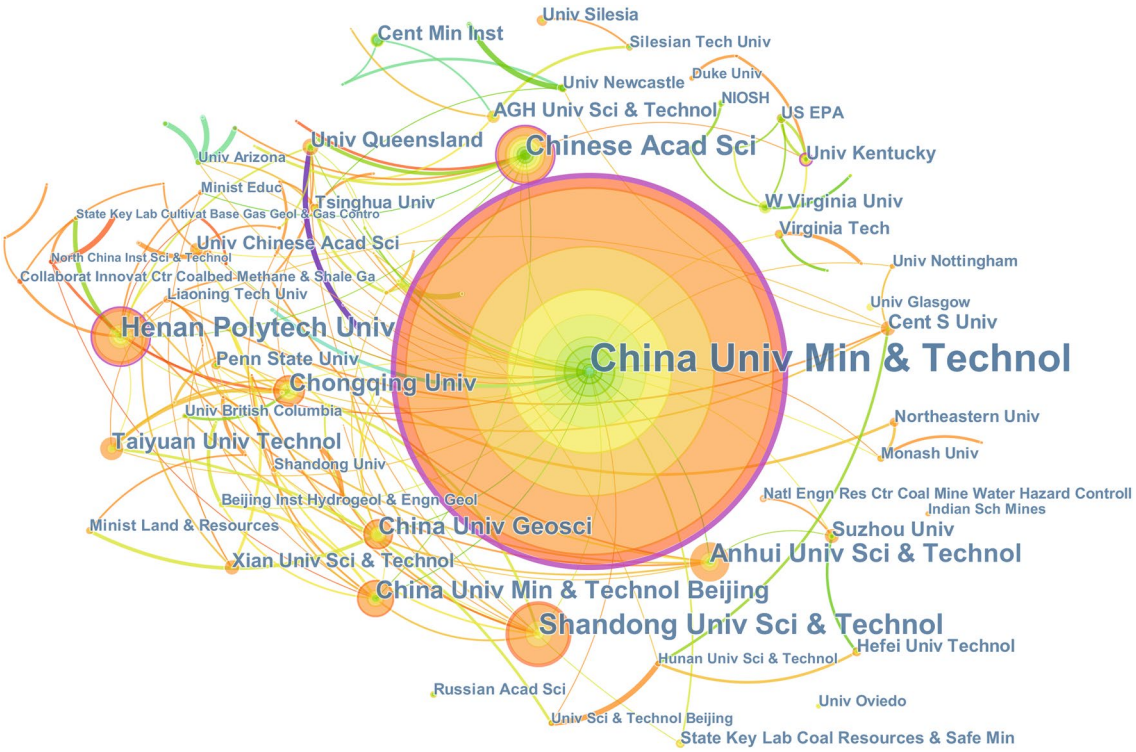

Fig. 3 The cooperation network of the most productive institutions in coal mine water inrush prevention and control during 2000–2019

published 62 articles. A number of other institutions are also making strong contributions to the field.

Categories Co-occurrence and Journal Co-citation Analyses

Disciplines involved in coal mine water inrush prevention and control research can be identified by analysis of subject category co-occurrence. The subject category information was extracted from tags of the WoS database by CiteSpace and then analyzed. The January 2000 to March 2019 co-occurrence network is illustrated in Fig. 4, where nodes represent a subject category and an edge connecting two nodes demonstrates the co-occurrence of the two subject categories, with strengths proportional to line thickness. Figure 4 indicates that engineering (488 extractions), geology (446), and multidisciplinary geosciences (424) are the top three research categories, followed by environmental sciences and ecology (375) and environmental sciences and water resources (349). Circle colours indicate timing (blue = oldest), with the earliest research involving mainly engineering and multidisciplinary geology and geosciences (Fig. 4). Centrality is only used to discover and measure the importance of the literature; the higher the centrality, the greater the importance of nodes, and purple circles are used to mark such nodes. Highly centralized nodes are usually the key hubs connecting two different areas. The ten most

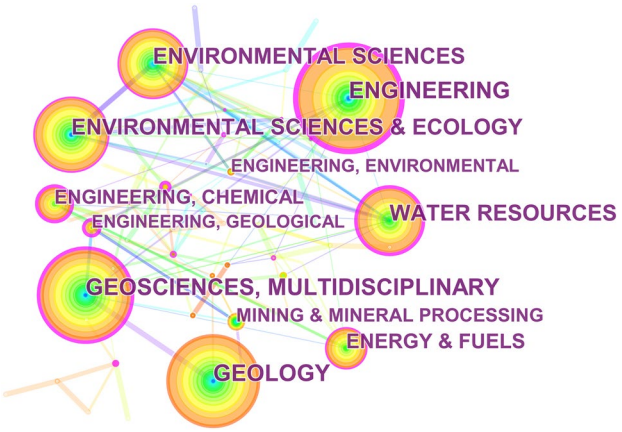

Fig. 4 The network of the subject category in coal mine water inrush prevention and control during 2000–2019

productive subjects are shown in Fig. 5. Engineering had the highest centrality, and geology was second, followed by multidisciplinary geosciences and then geological engineering. Coal-mine water inrush research is thus a multifaceted and multidisciplinary field covering a wide range of interests but with engineering and geology being the two major subject categories.

'Core journals' are those with high publication and co-citation counts, with knowledge maps providing information

on professional journals in a field. The top 10 scholarly journals that published articles related to coal mine water inrush prevention and control are listed in Table 1; these journals have an average impact factor (IF) of 2.66. Mine Water and The Environment, Environmental Earth Sciences, and the International Journal of Coal Geology have published the most articles in this field. The co-citation journal map (Fig. 6) displays 364 nodes (representing journals) and 785 links (representing collaboration links), with strength proportional to line thickness. The top five co-cited journals were the International Journal of Coal Geology, International Journal of Rock Mechanics and Mining Sciences, Engineering Geology, Environmental Earth Sciences, and Mine Water and the Environment, and the top five in terms of centrality were the International Journal of Coal Geology, Environmental Geology, Journal of Hydrology, Applied Geochemistry, and the International Journal of Rock Mechanics and Mining Sciences. Our analysis of publication and co-citation counts and centrality identified the International Journal of Coal Geology as the leading core journal in coal-mine water inrush research, with its published articles reflecting the fundamentals of the field (supplemental table S-4).

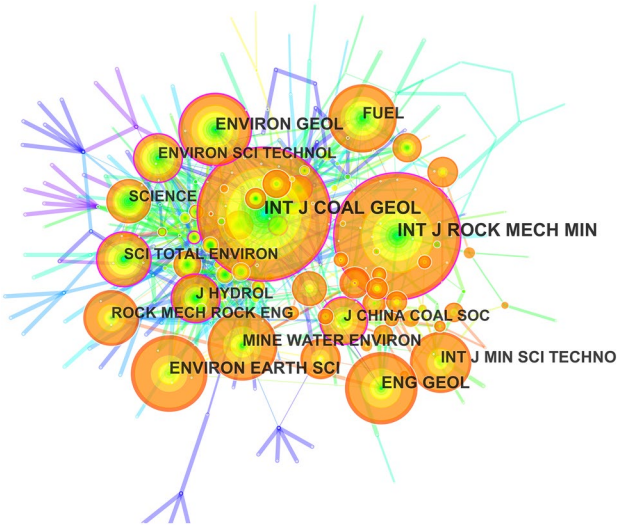

Fig. 6 The network of the scholarly journals in coal mine water inrush prevention and control during 2000–2019

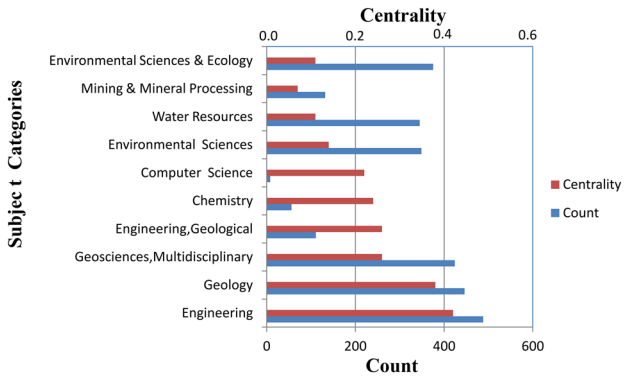

Fig. 5 Details for the top 10 subjects

Authors Co-occurrence and Co-citation Analysis

The mapping of 'productive creators' in coal mine water inrush prevention and control research includes 355 authors with 542 co-reference links (Fig. 7). The nodes represent authors and lines between nodes represent collaboration links with strengths proportional to line thickness. The principal authors are listed in supplemental table S-5). The centrality rankings are Wu Qiang (0.06), Liu Weitao (0.06), Ma Dan (0.05), Bai Haibo (0.05), and Li Wenping (0.04). The top five authors have publications of significant influence,

Table 1 The top 10 scholarly journals

Rank	Publications	Journal	IF(Q)(2018)	Percentage	Bar Chart
1	83	Mine Water and The Environment	2.145 (4)	5.14%	
2	65	Environmental Earth Sciences	1.435 (4)	4.03%	
3	63	International Journal of Coal Geology	4.130 (2)	3.90%	
4	53	Arabian Journal of Geosciences	0.860 (4)	3.28%	
5	33	Fuel	4.908 (2)	2.04%	
6	31	International Journal of Rock Mechanics and Mining Sciences	2.836 (3)	1.92%	
7	24	Advances in Civil Engineering	0.827 (4)	1.49%	
8	23	Energies	2.676 (3)	1.42%	
9	21	Journal of Natural Gas Science and Engineering	2.803 (3)	1.30%	
10	20	Science of The Total Environment	4.610 (2)	1.24%	

IF and Q are reported according to Journal Citation Reports (2018)

IF impact factor

and there are partial cooperative relationships among the authors. For example, Wu Qiang and Liu Shouqiang, Liu Weitao, Zhou Wanfang et al., and Ma Dan and Bai Haibo et al. are marked in Fig. 7, indicating bursts of articles of relatively high influence with high levels of attention by other authors during particular parts of the study period.

Figure 8 and Table 2 indicate authors with highest citation frequencies in this field. The nodes in Fig. 8 represent authors, lines between nodes represent collaboration links with strengths proportional to line thickness, and the different colours depicted the different time zones. Results indicate that some authors (e.g., Zhang) have a relatively small number of publications with high citation frequencies, implying that their studies were 'hot topics' with high levels of attention and influence. Some authors (e.g., Ma and Yin) have had strong bursts of publications with relatively high levels of attention during a certain period, with author influence not necessarily being determined by the number of publications alone.

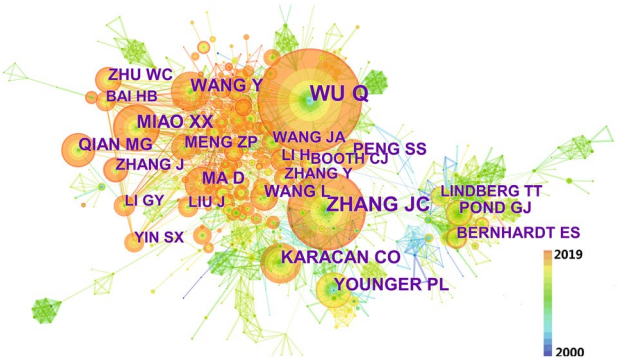

Fig. 8 The network map of co-cited authors contributed to coal mine water inrush prevention and control during 2000–2019

Co-occurrence of Keywords and Terms

The keywords permeability, model, and aquifer have large nodes (Fig. 9), and accordingly high centralities (Supplemental Table S-6), with visible system, seam, and permeability also being key elements. The dynamic evolution graph of keywords indicates that permeability, drainage, and risk assessment appeared successively during 2002–2008,

Fig. 7 The network map of active authors contributed to coal mine water inrush prevention and control during 2000–2019

Table 2 The top ten authors and co-cited authors

Rank	Co-cited authors	Count	Co-cited authors	Burst (2015–2019)
1	Wu Qiang	217	Ma Dan	10.64
2	Zhang jincai	122	Sun Wenjie	8.11
3	Miao xiexing	73	Li Shuncai	8.11
4	Karacan Co	63	Yin Shangxian	8.03
5	Ma Dan	53	Li Peiyue	6.79
6	Qian minggao	53	Lu Yilong	6.30
7	Syd S. Peng	49	Shi Longqiang	6.23
8	Zhang Yun	32	Li Bo	5.93
9	Yin Shangxian	31	Xu Jialin	5.72
10	Bai Haibo	31	Yang Wang	5.53

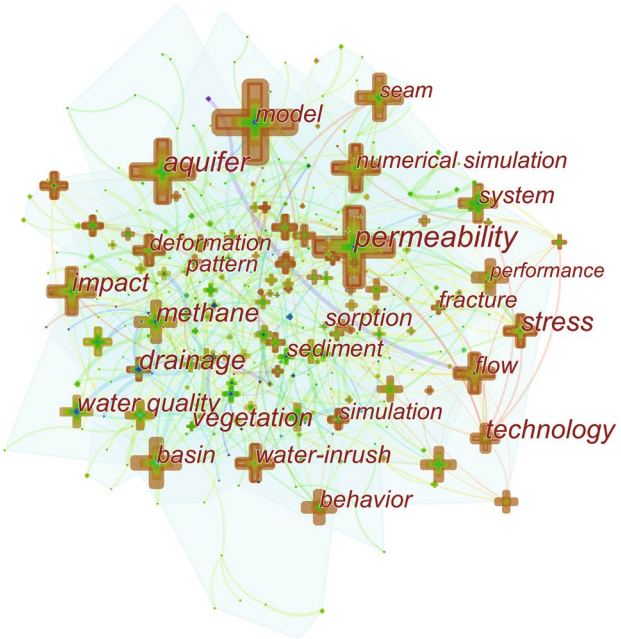

Fig. 9 The co-occurrence of keywords in coal mine water inrush prevention and control during 2000–2019

implying a shift from passive coal-mine flood studies to active prevention (Fig. 10).

Popular Research Topics and Trends

CiteSpace was used to capture burst keywords that might predict research frontiers. The new hot topics are indicated by a high number of citations in a short period of time. Node selection was based on keyword burst detection for 2000–2019 and produced an ordination diagram for the year of keywords with strong bursts (Fig. 11). The results show that electromagnetic method, analytic hierarchy process, coal seam floor and overlying strata, source identification, etc., had strong bursts in recent years, indicating that they are hot research topics. In Fig. 11, blue lines represent time intervals and red lines the period of citation bursts, leading to the identification of three frontiers in coal mine water prevention and control research, as follows.

1. Electromagnetic method was a burst keyword from 2017 to 2019. The electromagnetic method is an efficient method for detecting hidden water disasters at the workface (Shi 2013). Therefore, we consider that hidden water disasters, caused by separated layer water, collapse column, underground hidden river, hidden faults, etc., is a current research hotspot. Although some research results have been obtained with this type of water hazard exploration, it is far from being able to meet the needs of production, which is the current research difficulty in this field.
2. Analytic hierarchy process (AHP) was the second burst keyword from 2017 to 2019. (AHP) is the research method usually used to fuzzy quantify the qualitative index and then pursue quantitative evaluation. Some scholars use AHP to establish the hydrogeological concept model of water inrush of confined aquifer under coal mine (Wu et al. 2013a, b), trying to further improve the qualitative evaluation results, pursue the quantitative evaluation results. At present, AHP is one of the most important risk assessment methods (Hu et al. 2019) and has been used to forecast (Zhang and Yang 2018) water inrush from coal seams. However, its level of accuracy is still not satisfactory. Therefore, research is being used to strengthen aquifer quantitative evaluation, improve the level of coal mining safety, and liberate the restricted area coal.
3. Coal seam floor, overlying strata, and source identification were the next burst keywords from 2017 to 2019. Roof- and floor-water inrush events cause some of the worst accidents in underground coal mines (Liu et al. 2019; Yin et al. 2019). There has been much research on quantitative evaluation of aquicludes and floor-water hazards, with significant progress being made (Liu et al. 2018a, b; Li et al. 2018), but some problems remain unsolved. The rapid and accurate identification of water inrush source is very important for the prevention and control of water inrush from coal seam roof and floor and it is still a hot research topic.

These recent research trends indicate that:

1. Electromagnetic detection techniques based on the basic principle of electromagnetic induction are becoming increasingly more accurate in the detection of hidden disaster factors of water disasters.

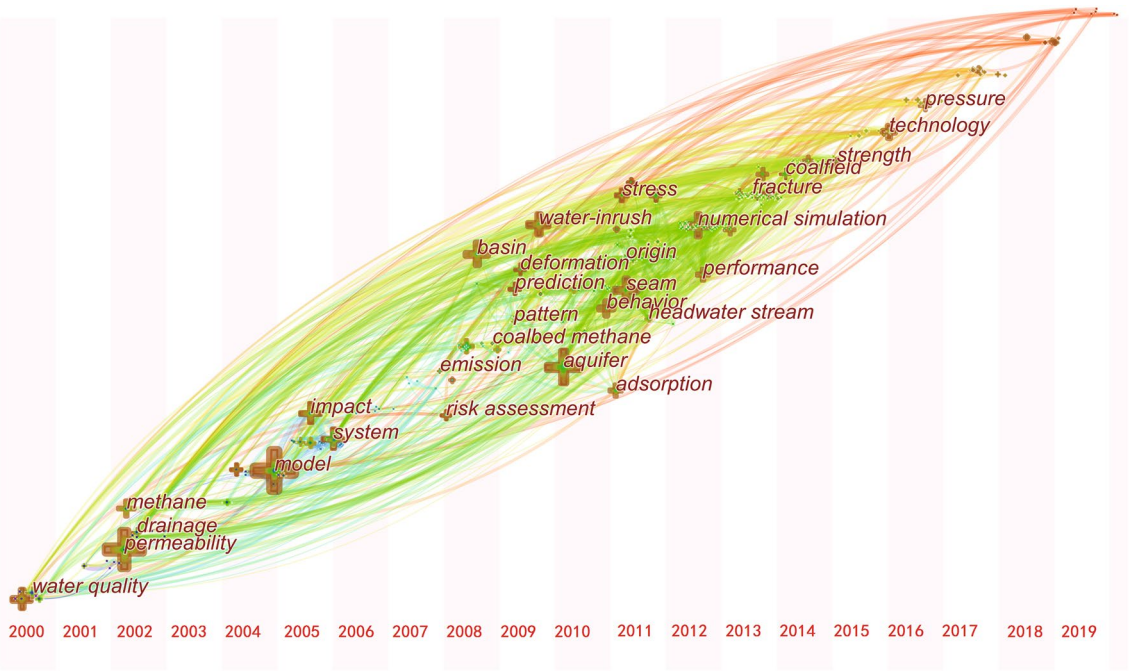

Fig. 10 The TimeZone of keywords in coal mine water inrush prevention and control during 2000–2019

Fig. 11 The keywords with the strong citation bursts in articles related to coal mine water inrush prevention and control research published from 2000 to 2019

Top 20 Terms with the Strongest Citation Bursts

Terms	Year	Strength	Begin	End	2000-2019
water quality	2000	3.3217	2004	2005	
coal mining	2000	7.2077	2004	2007	
coal mines	2000	5.0137	2005	2007	
coal seams	2000	4.4753	2005	2009	
underground mining	2000	3.2435	2008	2011	
upper silesian coal basin	2000	5.1612	2009	2014	
water level	2000	3.8709	2012	2016	
coal industry	2000	3.1667	2012	2014	
groundwater sample	2000	3.6524	2013	2014	
water pressure	2000	3.7236	2015	2019	
pore structure	2000	3.7717	2015	2017	
numerical simulation	2000	4.5967	2016	2018	
mechanical model	2000	5.2893	2017	2019	
risk assessment	2000	4.2077	2017	2019	
geological condition	2000	3.5281	2017	2019	
source identification	2000	3.9032	2017	2019	
overlying strata	2000	5.2893	2017	2019	
coal seam floor	2000	4.2741	2017	2019	
analytic hierarchy process	2000	4.1506	2017	2019	
electromagnetic method	2000	4.5298	2017	2019	

2. An intelligent mine water monitoring platform is being developed to digitize the characteristics of coal mine aquifer(s), provide accurate monitoring and early warning, and fundamentally improve the accuracy of risk assessment based on the rapid development of modern computer science and technology, the Internet of things, big data, and cloud computing. The latter two are already being used to better predict and avoid water disaster accidents. Driven by the real-time monitoring data of the Internet of things, the new platform is improving through self-learning to achieve real-time early warning of mine water hazards.
3. A more detailed and transparent three-dimensional hydrogeological system is being developed to effectively solve complex water inrush problems, such as inrush source identification. It uses a variety of geological means, geophysical and geochemical methods, and information technology to establish a three-dimensional geological information system that is able to rapidly query, analyse, and process these data and then make correct and reasonable decisions. Its core technology is visual spatial analysis and spatial data mining.

Conclusion

This scientometric review indicates that research on coal mine water inrush prevention and control developed rapidly during 2000–2019. China and the USA are the countries with the highest publication volumes in the field, with China, USA, Australia, the UK, and other high-publishing countries cooperating closely. The China University of Mining and Technology and Shandong University of Science and Technology are the two most influential institutions in the field, with the largest number of publications in coal-mine water-control research. Coal mine water inrush prevention and control involves cross-disciplinary studies in engineering, geology, water resources, environmental science, ecology, and other disciplines. Mine Water and the Environment, Environmental Earth Sciences, and the International Journal of Coal Geology are the journals published in English with the most papers on the topic. The International Journal of Coal Geology, International Journal of Rock Mechanics and Mining Sciences, and Engineering Geology are the journals with the research of greatest impact. Wu Qiang, Ma Dan, Gui Herong, and Bai Haibo are authors who have made significant contributions to the field. Hidden water disaster, quantitative evaluation of aquicludes, and rapid identification of water inrush source from coal seam roof and floor are current research hotspots. Improvement of electromagnetic methods, intelligent mine water monitoring platforms, and three-dimensional hydrogeological systems are research trends in this field, and researchers should pay close attention to relevant studies in the coming years.

The limitations of this study are recognized. The restriction of articles to the English language will have led to the omission of many articles, and the use of predefined terms could similarly have resulted in papers being overlooked. Also, reliance on the Web of Science Core Collection may have resulted in some one-sided conclusions.

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