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# Dynamic and Prospect of Substation Flood Control Risk Emergency Management Based on Visual Analysis

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**Abstract: To explore the research hotspot and development trend of substation in the field of "flood control, risk, emergency and management", based on the Web of Science core collection database, Citespace and VOSviewer analysis software were used to visually analyze the relevant literature from 2004 to 2023. The results showed that the annual number of published papers showed a gradual increasing trend. The author with the most publications is Wang LF from the United States (12), and Chinese institutions account for 60% of the top 10 institutions. Southwest Jiaotong University in China and University of Manchester in the United States have the most publications (22 and 17). The countries with the highest number of publications are China and the United States (270 and 149), but China's citation rate is lower than the United States; The research on keywords mainly focuses on management, optimization, model, system, algorithm and intelligent grid, etc. Keywords collinear time chart mainly focuses on development direction, management, risk assessment and security research. The substation flood response has changed from a single technical solution to the application of multidisciplinary integrated methods. China's influence in this area is growing.**

**Keywords: Substation; Flood; Risk; Emergency Management; Visual Analysis**

## 1. Introduction

Substation is a unit that constitutes the power system, one of the key facilities for safe and stable operation in the entire power grid, and a central hub station that connects the power source side and load side. In the entire power industry system, substations serve functions such as converting voltage levels, centralizing, and distributing electrical energy. They are not only an important link between users and the power grid but also a crucial aspect of safe and stable power transmission. In recent years, with the intensification of climate warming and the acceleration of the global water cycle, the frequent occurrence of extreme weather events has led to escalating meteorological disasters, posing a serious threat to the normal and stable operation of substations. The existing flood response methods may not be able to timely and effectively address the flood prevention issues faced by substations. Therefore, it is necessary to conduct research on operation and maintenance strategies and emergency response measures for substations of different types and flood prevention risk levels, taking into account practical situations[1].

Currently, researchers both domestically and internationally have conducted certain studies on substations, primarily focusing on safety operation and maintenance, risk assessment, and management. Ge and Asgarpoor proposed a stochastic reliability modeling method for substations based on aging equipment issues, providing a valuable tool for handling maintenance of individual components in aging equipment[2]. Guo Caishan et al. qualitatively analyzed the unestimable information caused by faults by constructing a failure tree for the relay protection system, identifying their risk types, and comprehensively considering the importance of primary intervals and the severity of relay protection faults in risk assessment. The results showed that the proposed method could effectively analyze the risk impact caused by relay protection faults[3]. Antonijević et al. used a new hybrid convolutional neural network and adjusted long short-term memory technology to

study the operation and maintenance management of substations. They extracted features through linear discriminant analysis (K-LDA) and improved the effectiveness of the method using genetic algorithms. By comparing the performance of this technology with specific current models, the method was significantly enhanced in substation operation and maintenance management[4]. However, there are still certain deficiencies in the research on flood prevention risk emergency management for substations, including a lack of summaries and analyses of the current research status and application trends in flood prevention, risk, emergency, and management. There is also a lack of visual research using bibliometrics and analysis methods. Summarizing and analyzing these studies can help researchers grasp the overall level of this field, quickly and effectively find literature, and lay a foundation for further research. Based on the Web of Science core collection database, this paper retrieved and summarized literature from 2004 to 2023. Using scientific research analysis software Citespace and VOSviewer, it analyzed the current research status, frontier hotspots, and development trends in the fields of flood prevention, risk, management, and emergency response for substations, laying a foundation for the implementation of flood prevention risk emergency management for substations.

## 2. Data and Methods

### 2.1 Data Sources

This article employs bibliometric methods utilizing Citespace and VOSviewer to conduct a search and quantitative analysis of relevant literature pertaining to flood control emergencies and risks in substations within the Web of Science (WoS) core collection database. The WoS core database is searched using the following themes: TS=("substation" AND "flood") OR TS=("substation" AND "risk") OR TS=("substation" AND "emergency *") OR TS=("substation" AND "management"). The search covers the period from 2004 to 2023. The selected literature is exported in plain text format, with "fully recorded and cited references" serving as the sample for data analysis (refer to Figure 1). Through the application of Citespace software, duplicate literature and non-academic articles are eliminated, ultimately retaining 882 WoS articles.

### 2.2 Analysis Method

Citespace and VOSviewer software visualize data samples to present the evolution process of specific knowledge domains, and can illustrate the relationships between literature in the form of a scientific knowledge graph. Among them, the author's article distribution, research institution analysis, research country distribution, and keyword collinearity maps were analyzed using VOSviewer software, while the development trends and hot spot changes were constructed using Citespace software. The annual publication volume is based on software R 4.3.2.

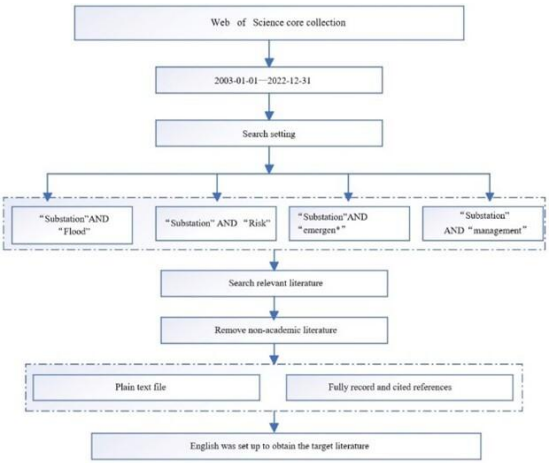


**Figure. 1 Flow Chart of Literature Retrieval**

## 3. Discussion

### 3.1 Annual Publication Volume

The number of published papers reflects the degree of attention and change trend of relevant researchers in this field. Based on the literature search statistics from the WoS Core Collection database (Figure 2), the papers on emergency management of flood risk in substations can be roughly summarized into three periods: The first stage (2004-2011): The number of publications gradually increased, but the growth rate was limited, ranging from 7 to 19 publications per year. During this stage, research in the field of substations was relatively slow, with content mainly focusing on traditional energy fields. The second stage (2012-2017): Starting from 2012, research in the field of substations ushered in a significant growth period. During this period, the number of publications showed a clear upward trend, increasing from 22 in 2012 to 52 in 2017, with a significant increase,

reaching an average of 42 publications per year. The third stage (2018-2023): Since 2018, research in the field of substations has entered a period of rapid growth, with a significant increase in the number of publications, rising from 81 in 2018 to 126 in 2020, and continuing to climb to 153 in 2023. Globally, there has been a continuous increase in awareness of the impact of climate change and natural disasters. Additionally, cybersecurity and data privacy issues have also become one of the concerns in flood emergency risk management to ensure the stable operation and data security of substations during disaster events.

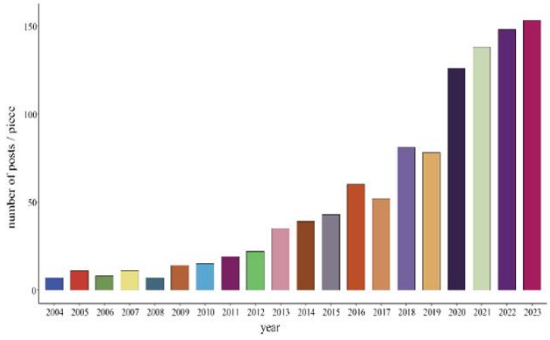


**Figure. 2 The Annual Distribution Trend of the Number of Publications**

### 3.2 Author's Distribution of Publications

The authorship situation is an important external feature reflecting the maturity of researchers in a certain field. Using VOSviewer software, we selected authors who have published more than 2 papers in this field, and found that a total of 402 authors meet the criteria. The results are shown in Figure 3. Among them, the author with the highest number of publications is Wang Lingfeng from the United States, with 12 papers, mainly involving substation network risk management, substation risk transfer tools, substation network insurance business, and topology configuration of high-voltage distribution networks[5-6]. The second-ranked authors are Xie Qiang from Tongji University in China and Chen Minwu from Southwest Jiaotong University, both with 9 papers. Xie Qiang's research focuses on equipment coupling effects, numerical simulation, and risk analysis[7-9]. Chen Minwu's research involves mathematical models, flexible control, photovoltaic and hybrid energy storage systems, etc[10-11]. The fourth-ranked author is Ten Chee-Wooi from the University of Michigan in the United States, with 8 papers, mainly studying substation network security, resource optimization and allocation, and risk measurement[12-14]. Yang Zhongping from Beijing Jiaotong University, Ustun Taha Selim from Fukushima Renewable Energy Research Institute in Japan, Siano Pierluigi from the University of Salerno in Italy, Liu Zhaoxi from the University of Wisconsin in the United States, and Lehtonen Matti from Aalto University in Finland all have 7 papers, covering topics such as substation traction power supply systems, three-phase to single-phase converters, fuzzy logic control, ground energy storage systems, Markov models, smart substations, risk assessment, capacity optimization planning, and fault management systems[15-19].

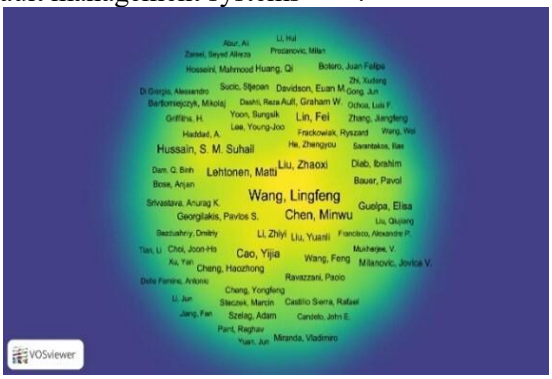


**Figure. 3 Contribution Map of Authors**

**Table 1 Lists the Top 10 Authors Cited**

| Serial number | Cited quantities | Connection strength | Cited Author |
|---|---|---|---|
| 1 | 64 | 411 | Billinton R |
| 2 | 60 | 350 | Guelpa E |
| 3 | 56 | 418 | Wang Y |
| 4 | 50 | 559 | Ciccarelli F |
| 5 | 49 | 524 | Panteli M |
| 6 | 48 | 213 | Lund H |
| 7 | 43 | 295 | Baran Me |
| 8 | 42 | 445 | Iannuzzi D |
| 9 | 42 | 492 | Ustun Ts |
| 10 | 41 | 352 | Li Y |

Co cited authors refer to authors who are cited in one or more articles simultaneously. By analyzing co cited authors, we can understand their importance and influence in specific fields. By counting the top 10 cited authors, it can be seen (Table 1) that from 2004 to 2023, the top three authors in terms of co citation frequency are Billington R Guelpa E、Wang Y。 Among them, the highest number of citations for Billington R in Canada is 64, indicating its strong influence in the field of substation flood risk emergency management. Its article mainly studies circuit aging, Markov models, Monte

Carlo simulation, and rapid reliability assessment[20-21]. Next is Guelpa E from Italy, which has been cited 60 times and mainly researches automatic modeling and detection of substations[22-23]. China's Wang Y ranks third with 56, mainly focusing on energy management strategies for substations, emergency power supply for power supply systems, and high-voltage fault diagnosis[24-26]. In addition, Ciccarelli F has the highest connection strength, indicating that its paper has a high influence in terms of citation. Its paper mainly involves energy storage systems and voltage control[27].

### 3.3 Research Institution Analysis

By analyzing research institutions in VOSviewer, important information about the development of scientific research fields, collaborative networks, and knowledge dissemination can be obtained, thereby promoting communication, cooperation, and innovation in scientific research. Based on the fact that among 1407 institutions in this field, the institution with the largest number of papers is Southwest Jiaotong Univ in China with 22 papers, followed by Manchester University in the United States and Islamic Azad Univ in Iran with 17 papers. It is worth noting that in the 20 years of research before 2022, Manchester University in the United States has always ranked first in the number of papers issued by research institutions in this field, with 17 papers, and Southwest Jiaotong Univ is 15 papers, ranking second. In 2023, Southwest Jiaotong University surpassed Manchester in the United States in the number of five papers, ranking first, indicating that the strength and influence of Chinese institutions in this field are gradually growing. The fourth and fifth ranked institutions are North China Electric Power University and Tongji University in China, both with a total of 16 papers. Among the top 10 institutions, Chinese institutions account for 60%, indicating that China has great potential for latecomers in the field of substation flood prevention risk emergency management. And there are many research institutions, reflecting the continuous improvement of China's scientific research strength and response capabilities in this field.

### 3.4 The Distribution of Study Countries

The number of publications in this field by a country to some extent represents its level of attention. According to the search results of WoS (Figure 4), the top 10 countries in terms of literature volume in the field of substation flood risk emergency management are China, the United States, the United Kingdom, Italy, Iran, India, Spain, Brazil, Canada, and Australia. These countries have published a total of 874 articles, accounting for 63.89% of the total number of national publications. Among them, China and the United States have published 270 and 149 articles respectively, accounting for a total of 30.63%, which is much higher than the publication volume of other countries. In addition, the United States (3601), China (2914), the United Kingdom (2382), Italy (2028), and India (1232) have high citation rates in this field and are countries with significant influence in the field of substation flood risk emergency management. China has a higher number of publications than the United States, but its citation rate is not as high as that of the United States, indicating that China's cooperation with other countries/regions still needs to be strengthened, and there is still a certain gap in its international influence compared to the United States. High level influential papers still need to be enhanced.

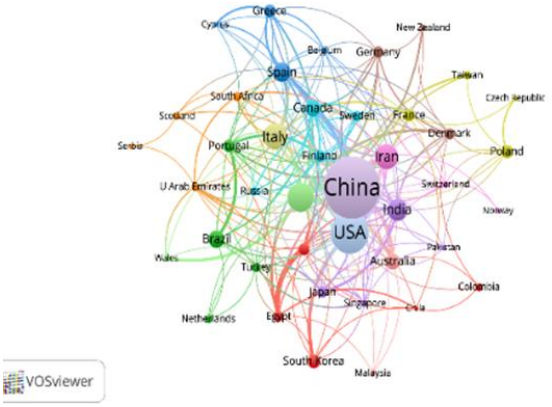


**Figure. 4 Distribution Map of Sample Literature Study Countries from 2004 to 2023**

### 3.5 Keyword Collinearity Analysis

Keywords are highly summarized of the core content of an article, and conducting collinear analysis of keywords can help to understand the hot topics and trends in the field of research. In VOSviewer, by selecting keywords based on node types, a keyword collinear network graph is obtained as shown in Figure 5. The circle nodes represent the frequency of keywords, and their activity level is positively correlated with the size of the circle. From Figure 5, it can be

seen that from 2004 to 2023, the top 10 hotspots of attention in the field of flood risk emergency management for substations, excluding substations, are management, optimization, model, system, reliability, generation, smart grid, algorithm, power, IEC 61850, etc. This indicates that the research hotspots in this field mainly include safety operation and maintenance management of substations, model optimization, intelligent network distribution, etc. At present, there are relatively many articles on substation management and optimization. For example, Gungor et al. have elaborated on the relevant issues of smart grid architecture from the perspective of system management[28]. Antonijevic et al. proposed a new monitoring control and data acquisition visualization process to enhance and promote human centered activities in substations, such as regular equipment maintenance for intelligent management[29]. Peter et al. used optimization algorithms to optimize the maintenance planning process and actual performance, including the reliability of power system operation, maintenance costs, and related risks[30]. However, the risk assessment and flood prevention of substations rank 18th and 29th respectively, relatively low in ranking, indicating that the research attention in the field of substation flood prevention is not yet too high. In recent years, with the emergence of extreme weather, the safety of substations has been challenged, and the study of substation flood prevention risks may gradually become a hot topic of concern.

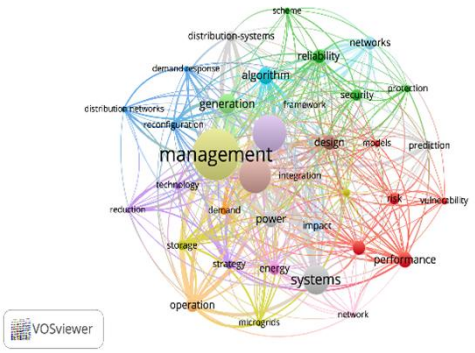


**Figure. 5 Research Hotspot Knowledge Map**

### 3.6 Development Trends and Hot Spot Changes

The collinear timeline chart of keywords aids in comprehending the development, evolution, and research progress of various clustered hot keywords within the substation research domain. It categorizes them based on the research themes they pertain to, examines the detailed content of each cluster, and utilizes different colors for nodes and lines to represent various time slices. The positions of nodes indicate when keywords emerge during different time frames. By utilizing Citespace software, we project the keyword knowledge graph onto the timeline, choosing a 2-year interval as a time slice, and illustrate a key time zone map for substations in this research area. The outcomes are exhibited in Figure 6.

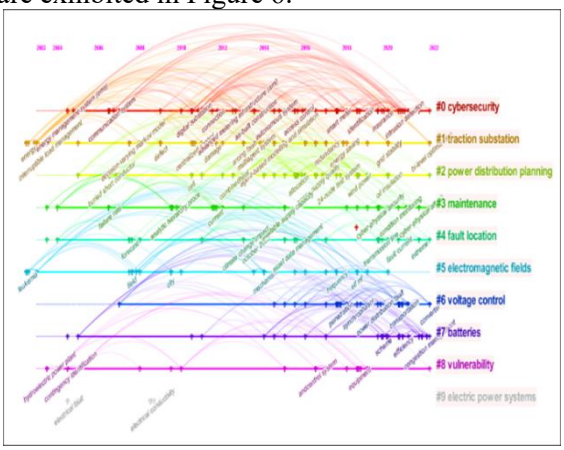


**Figure. 6 Time Graph of Keywords in Highly Cited References**

The research on constructing a flood prevention risk emergency management system for substations, as illustrated in Figure 6, encompasses 10 clusters. Among these, #1 traction substation and #9 electric power systems serve as the fundamental clusters. This research topic signifies the developmental trajectory of substations, with key research areas encompassing centralized control, multi-agent systems, conductivity, and electrical faults. Early investigations primarily centered on the foundational theories of power systems and traditional substations. However, with the advancement of smart substations and the integration of intelligent technology, researchers have increasingly shifted their focus to power substations and their related domains. Power substations, besides fulfilling the roles of conventional substations, are capable of efficiently managing and dispatching renewable energy, as well as controlling and overseeing energy storage devices. To address the overload resulting from the phased replacement of rectifier units in subway traction substations, Vlasov and colleagues proposed modifying the secondary voltage of the converter transformer.

Through modifications to the traction substation, they put forth specific recommendations for altering the secondary voltage during the concurrent operation of multi-pulse rectifier circuits[31].

The research on substation management encompasses #0 cybersecurity, #2 power distribution planning, and #6 voltage control. This research topic exhibits good continuity in the field of cybersecurity. The clustering of distribution and voltage research is relatively recent with a shorter time span. Nevertheless, the numerous keyword nodes on the horizontal axis of the timeline graph indicate that substation management has garnered increasing attention from researchers in recent years. The management and maintenance of substations may still emerge as a hot research topic in the future. The main research topics include digital substations, power management, safety, connectivity, converters, etc. With the continuous development of information technology, the increasingly close connection between substations and external networks poses new challenges to network security. Formulating reasonable and efficient power distribution plans can minimize energy losses and enhance the reliability and stability of the entire energy system. Voltage control is also an important direction in substation management research. Maintaining a stable voltage level during substation operation is crucial for ensuring the quality of electricity used by users.

Substation risk assessment and safety research encompass clusters #3 maintenance, #4 fault location, #5 electromagnetic fields, #7 batteries, and #8 vulnerability. This research primarily delves into the risks associated with substations and strategies to mitigate faults and vulnerabilities. Historically, this topic was addressed earlier, but in recent years, the focus has shifted towards maintenance and battery safety performance. This shift is attributed to the crucial role of maintenance in ensuring the smooth operation of substation equipment. Regular maintenance and upkeep can effectively diminish the likelihood of equipment malfunctions and accidents. To tackle the challenges of inadequate control, safety measures, and data management during substation maintenance and operation, Zhu et al. introduced an intelligent control platform for comprehensive substation maintenance and operation, leveraging edge perception. This innovation has enhanced the efficiency of substation maintenance site operations[32]. Mileta and Zlatan harnessed artificial intelligence to assess operational risks using readily available information. They proposed a method for identifying interventions for high-voltage equipment through thermal imaging. Additionally, they refined the minimum path and minimum cross-section methods into fuzzy algorithms, thereby analyzing the performance of high-voltage substations[33].

### 3.7 Literature Analysis on Flood Prevention Response in Substations

Due to the scarcity of research on flood prevention in substations in the aforementioned studies focusing on keywords, authors, institutions, and national studies, further analysis of relevant literature on flood prevention in substations revealed that its content mainly involves models, simulations, emergency technologies, and risk control in the field of substation flood prevention. The results are shown in Table 2.

From Table 2, it is evident that the primary research methods for flood prevention in substations encompass Markov, particle swarm optimization, line-flooding algorithm, linear programming, stochastic optimization, among others. Yao et al. conducted a study on the reliability assessment of substation walls under flood conditions. They employed a complex numerical model, grounded in actual engineering data, to evaluate their bearing capacity. They recommended the adoption of a "W-shaped" wall reinforcement method, aiming to effectively minimize displacement and stress. These insights hold significant importance for the design and flood resistance of substations, underscoring the criticality of safeguarding internal facilities during floods[40]. Thai et al. focused on the impact of Typhoon “Aulu” (2022) on power outages in approximately 3200 substations located in central Vietnam. Utilizing the ocean-atmosphere-wave-sediment coupled transport (COAWST) model as input, they conducted a secondary analysis of the nearshore meteorological field through numerical simulation. The simulation outcomes provided invaluable support for the early warning system and troubleshooting efforts related to typhoon impacts[48]. Souto et al. integrated quantitative indicators and reinforcement strategies to

propose a mid-term power system resilience model, aimed at enhancing substations in flood-affected areas. This model was effectively validated[37]. Dullo et al. employed a hydrodynamic inundation model to assess the potential impacts of future climate change on flood conditions, floodplain protection, and power infrastructure of the Conasauga River in the southeastern United States[39].

From the publication time of literature, the field of substation flood prevention has shifted from a single technical solution to a comprehensive system analysis and multidisciplinary integrated method, as well as an emphasis on resilience. These developments have improved the predictive, preparedness, and recovery capabilities of substations for flood disasters.

**Table 2 Related literature of substation flood control**

| Serial Number | Time | Literature | Key words |
|---|---|---|---|
| 1 | 2009 | Shen[34] | Radiographic image; adaptive thresholding method; defects; line-flooding algorithm |
| 2 | 2009 | Sultana[35] | Infrastructure; Interdependency; Extended Petri net; Fragility curves; Flood hazard; Markov Chain; Emergency management |
| 3 | 2012 | Mcmaster[36] | Command and control; Communications; Emergency services; Sociotechnical systems |
| 4 | 2016 | Powell[37] | Risk analysis; Risk management; OR in disaster relief; Critical human activity systems; Qualitative system dynamics |
| 5 | 2016 | Reed[38] | Structural safety and reliability; Resilience; Interdependency |
| 6 | 2018 | Scott[39] | Adaptation; Hydrometeorological risk; Infrastructure; Interdependence; Risk reduction |
| 7 | 2020 | Yan[40] | Small hydropower; Voltage quality; Particle swarm algorithm; Coordinated control; Renewable energy |
| 8 | 2021 | Andrea[41] | SPH; Urban floods; dam breaks; Substation-flooding damage model; Electrical substations |
| 9 | 2021 | Movahednia [42] | Flooding; Grid resilience; Power substations; Resource allocation; Stochastic optimization |
| 10 | 2021 | Dullo[43] | Probable maximum flood; Impacts; Projections; Vulnerability; Resilience; Systems |
| 11 | 2021 | Daniel[44] | Electrical substation; GIS; Risk assessment; Cost assessment; Flooding; Resilience |
| 12 | 2021 | Zhu[45] | Cost-benefit analysis; Disasters; Infrastructure hardening; Markov decision process; Resilience |
| 13 | 2022 | Souto[46] | Critical infrastructure; Extreme weather; Flood; Mixed-integer linear programming; Optimization; Power system planning; Power transmission system; Resilience; Resiliency; Substation |
| 14 | 2023 | Yao[47] | Flood load; Prefabricated perimeter walls in substations; Stress characteristics; Force transmission mechanism; “W-shaped” reinforcement |

## 4. Summary and Outlook

In recent years, extreme meteorological disasters, such as strong winds and rainstorms, have affected transmission lines, switchgear, insulators, and other equipment in substations, thereby increasing the risk of equipment failure. This could potentially lead to power interruptions, causing inconvenience and even danger to users. Utilizing the WoS database, we conducted research on flood prevention, risk management, emergency response, and management from 2004 to 2023. We employed Citespace and VOSviewer for visual analysis, and arrived at the following conclusions and recommendations.

1) In terms of time distribution, research on flood risk emergency management in substations has undergone three distinct phases over the past 20 years: a slow development phase from 2004 to 2011, a significant growth phase from 2012 to 2016, and a rapid growth phase since 2017. This suggests that several countries and governments are increasingly

focusing on managing and responding to risks related to substations, with researchers' interest gradually increasing.

2) Analyzing the number of publications and co-cited papers by authors, Wang Lingfeng from the United States stands out with the highest number of publications, totaling 12. This underscores the need for further attention and in-depth research in this field. Between 2004 and 2023, Billinton R from Canada received the highest number of co-citations, totaling 64, indicating his significant influence in the field of substation flood risk emergency management. This is followed by Guelpa E from Italy and Wang Y from China, with 60 and 54 co-citations, respectively.

3) Regarding literature institutions and their national distribution, among 1407 institutions, the top three are Southwest Jiaotong University, the University of Manchester in the United States, and Islamic Azad University in Iran, with 22, 17, and 17 publications respectively. Chinese institutions account for 60% of the top 10, indicating a deepening of Chinese research in this field. The top ten countries by literature volume are China, the United States, the United Kingdom, Italy, Iran, India, Spain, Brazil, Canada, and Australia. These countries have published a total of 497 articles, with China leading the United States in publications at 270 to 149. However, China's citation rate is lower than that of the United States, suggesting that China's collaboration with other countries/regions needs to be enhanced.

4) Studying keywords reveals research trends and hotspots in this field. The collinear analysis of keywords indicates that, besides substations, the top ten concerns in flood risk emergency management include management, optimization, modeling, systems, reliability, generation, intelligent grid, algorithms, power, and Iec 61850. The keyword collinear timeline chart aids in understanding the evolution and progress of various clustering hot keywords in substation research, primarily focusing on basic research, management research, risk assessment, and emergency safety research. The literature on substation flood prevention is relatively scarce, mainly involving models, simulations, emergency technologies, and risk management.

In the future, with the occurrence of extreme events, the emergency management of flood prevention risks in substations has become an increasingly important issue for countries and governments. In order to improve the risk monitoring and early warning system and enhance the level of disaster prevention, reduction, and relief, researchers need to continue to pay attention to the emergency management of flood prevention risks in substations, strengthen the construction of prevention, monitoring, and emergency response capabilities, and minimize the occurrence of natural disasters.

**Acknowledgment**

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