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The Early Identification of Flash Flood Disasters: Mechanism, Model and Uncertainty

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Abstract

Flash flood disasters are one of the major natural disasters in the world, and rapid and accurate early identification of flash flood disasters is the key to preventing and controlling them. In recent years, computer and spatial information technology development has promoted the advancement of early identification technology for flash floods. However, previous research has mainly focused on the impact of "water" and neglected the impact of "sediment" deposition on the rise of water levels. To gain a more comprehensive understanding of flash floods and improve the accuracy of early identification, this article first uses bibliometric methods to review the spatiotemporal distribution, internal relationships, and research hotspots of literature in this field over the past 42 years. Then, the research practice of considering the impact of sediment on the early identification of flash floods was introduced from three aspects: mechanism, model, and uncertainty. Finally, the existing problems in current research were discussed, and future research directions were proposed. The research results have shown that the number of publications in this field has been increasing yearly and will continue to increase, but the cooperation between authors is not close. The coupling effect between sediment replenishment and floods cannot be ignored. Taking into account multiple uncertainties can greatly improve recognition accuracy. This study can provide a panoramic literature perspective and practical research experience for relevant researchers and decision-makers and support further improving flash flood prevention and control capabilities.

Keywords: flash floods, early identification, bibliometrics, mechanisms, data driven, hydrodynamics, conceptual model, uncertainties.

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1 Introduction

The flash flood disaster is a typical global major natural disaster (Duan et al., 2016; Chinh et al., 2023), and the casualties (Convertino et al., 2019) and socio-economic losses (Sathya et al., 2021) caused by it every year account for a high proportion of all kinds of natural disasters. The flash flood events are widely distributed, with the characteristics of high nonlinearity, randomness, complexity, and concealment (Tu et al., 2020), and will continue to show an increasing trend in the future (Yan et al., 2021), which puts forward a strong demand for the study of flash flood disasters. The first phase of flash flood prevention and control is the early identification of disaster-prone areas (Li et al., 2021), which can be taken as an economical and effective prevention means of flash flood disasters to estimate the time, place, and scope of future flash floods (Costache et al., 2020).

In recent decades, researchers have developed various early identification models based on the mechanism of flash flood disasters and have achieved significant results (Panahi et al., 2021; Suwanno et al., 2023). Although these early identification techniques are effective to a certain extent, the study of early identification of flash floods remains challenging due to the complex formation mechanism of flash flood disasters. Scholars with a great interest in this field have published many related research papers. Unfortunately, however, very few review papers are still in this field. Few people can make a systematic analysis based on bibliometric analysis and research practice, which makes it difficult to figure out the development process, research hotspots, and future research directions in this field. Despite this, we made objective statistics on applying GIS and RS in flash floods through bibliometric analysis (Ding et al., 2021). However, this is only an application analysis of the two technologies rather than a comprehensive review of early identification technologies. In 2022 (Yang et al., 2022), we began to focus on the research of early identification technology of flash floods, roughly sorted out the development process of this field by combining meta-analysis with visual analysis, initially established the knowledge framework for the research and provided future research directions. The prevention and control of most traditional flash flood disasters focus solely on the role of rainstorms in triggering floods (Liu et al., 2022) but do not consider the factor that local sediment deposition will raise the water level, resulting in insufficient accuracy in the early identification of flash flood disasters (Wang et al., 2019). Many cases of flash flood disasters (Gan et al., 2018) proved that the coupling effect of sediment and flash flood is the key factor triggering flash floods and often leads to “small floods and big disasters”. For example, a mountain flood disaster in Puge is typical. In the same rainstorm, the left mountain gully was silted up due to excessive sediment deposition, which led to the rise of the water level, and 25 people were killed when the river diverted. However, the mountain ditch on the right did not cause any disasters due to only floods and no sediment (Wang et al., 2019). Sediment accumulation raises the water level, causing general (medium and small) floods in mountainous rivers to suddenly increase sharply to the water level corresponding to floods that occur once every 50 years or even once every 1000 years, exceeding the local flood control standards. On the other hand, sediment accumulation causes local river blockage, leading to a sharp adjustment of the riverbed shape, changing the river regime and water flow conditions, and causing water and sediment disasters far greater than the effects of floods. Therefore, sedimentation is crucial for preventing and controlling flash floods. The significance of mastering this knowledge lies in combining nonengineering measures such as early identification techniques with engineering measures to reduce mountain flood disasters' water sediment coupling effect to a controllable range, providing an effective technical approach for predicting and warning mountain flood disasters. For this purpose, in recent years, we have carried out a series of systematic studies on the runoff generation and sediment yield, water-sediment movement, gully bed evolution, disaster-causing mechanism, and disaster-forming mode of flash floods. As shown in Fig. 1, seen from left to right, the range and intensity of natural external forces gradually decrease, while the range and intensity of human actions increase progressively. If each node on this chain can be controlled well, the losses caused by disasters can be reduced as much as possible (Li et al., 2021).

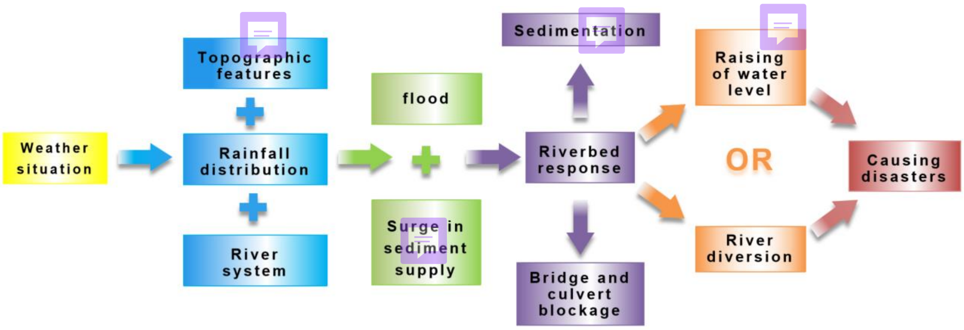


Figure 1. Complete chain of disaster caused by coupling of mountain torrents, water and sediment：The first column represents the triggering factors of flash floods in the weather situation (yellow); the second column represents environmental factors such as topographic features, rainfall distribution, and river systems (blue); the third column represents processes such as flood and Surge in sediment supply (green);

the fourth column represents the response of riverbed such as Sedimentation or Bridge and culvert blockage (purple); and the fifth column represents losses such as raising of water level and river diversion (red). Subsequently, the range and intensity of natural external forces gradually decreased, with the sixth column indicating the impact of disasters, and the range and intensity of human influence increased during this process. Adapted from Li et al. (2021).

The main objective of this paper is to build an updated and more extensive document sample database of early identification technology of flash floods, systematically sort out the internal relations of the documents, objectively analyze the development process and predict the development trend of this field, improve the research framework, and reveal the potential mechanisms and early identification methods of flash floods from the perspective of “water-sediment” based on our research practice. This paper is organized as follows: The first part introduces the research background of early identification technology of flash floods; the second part establishes the document sample database based on Web of Science (WOS for short) and Scopus platforms, and introduces the bibliometric analysis used; the third part clarifies the overall trend of documents published, spatial-temporal distribution and key research directions of this field through document characteristic analysis, co-word analysis and cluster analysis; the fourth part takes the joint action of flood and sediment as the starting point to explore the research progress of early identification technology of flash floods based on our research practice and the impact of sediment on flash floods: i) reveal the flash flood and sediment coupled disaster-causing mechanism (typical disaster-causing locations: steep-gentle transition reach, tributary confluence reach, curved reach, bridge and culvert reach); ii) propose the early identification methods for flash flood disasters (based on data-driven intelligent models and hydrodynamic models), and increase the coverage of early identification to over 40%; iii) analyze the uncertainty affecting early identification accuracy. In the end, this paper discusses the current major challenges and research gaps in this field and puts forward some suggestions for key issues (e.g., expansion of disaster-causing mechanisms of wide and narrow reaches, the broad prospect of applying models based on knowledge mapping, careful consideration of multiple uncertainties) to improve the accuracy of early identification results. The systematic review and gap identification use bibliometric tools to analyze the research status of existing literature, and the qualitative or quantitative research results formed will help improve the knowledge system of mountain flood disasters. Researchers and decision-makers can identify this article's current research focus and shortcomings and obtain some suggestions. In addition, a panoramic knowledge integration service can be brought to save research time.

2 Establishment of the document database and methodology

To establish a document database, as shown in Fig. 2, the keywords of "flash flood*" and "identify*" as well as the Boolean search criteria AND were first used to retrieve the core collections in the online platform of "Web of Science" and the peer-reviewed articles in "Scoups". The search range included title, keyword, and abstract, and there was no restriction on the language. Then, the lists of references in all selected articles were checked and retrieved repeatedly from July 2022 to August 2023 to obtain a preliminary list of 2,240 articles.

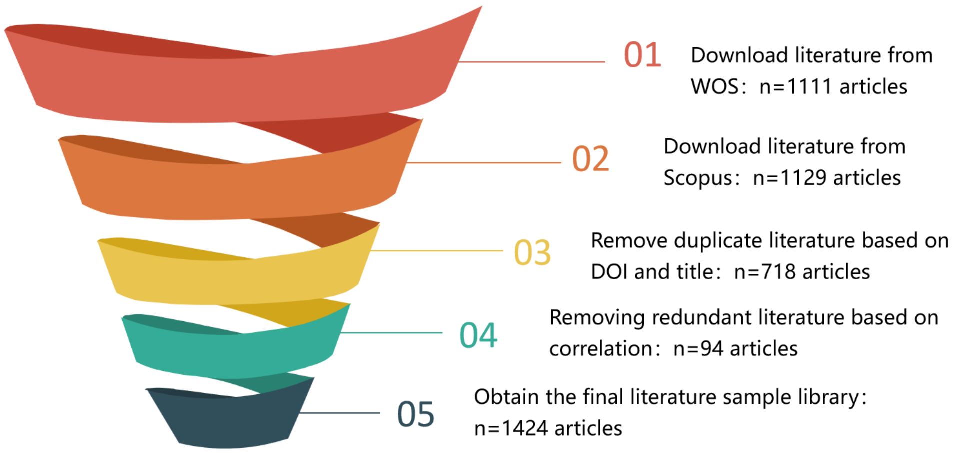


Figure 2. Construction process of literature sample library.

Next, the articles in the preliminary list were thoroughly examined, and 718 duplicate documents with the same DOI and title were removed. A total of 94 uncorrelated or weakly correlated documents were manually excluded one by one. The keywords in the exclusion criteria included isotope, disease, microorganism, arsenic concentration and, cytology, etc. The final document sample database listed 1,424 articles published from January 1,1981 to August 18, 2023. The literature database uses both text data format (*. ris, *. txt) and table data format (*. xls) for storage. The text data format is the standard format required by the metrology software, and the table format can be customized as shown in Table 1.

Table 1
Establishment status of the document database.

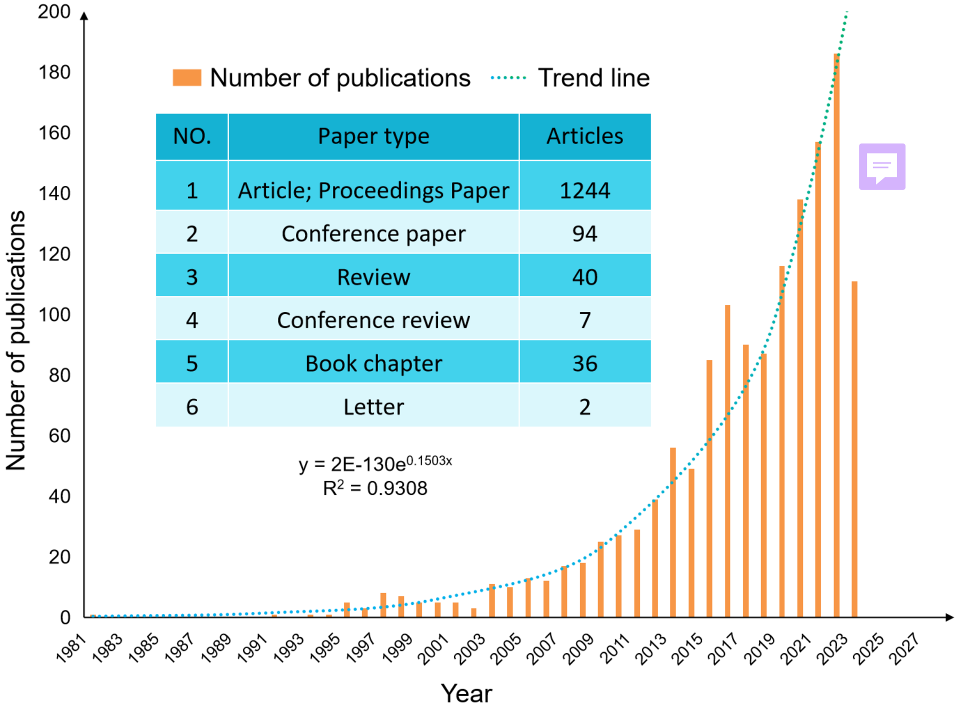
Type	Data platform	Authors	Article Title	Source Title	Abstract	Times Cited
Article	WOS	Prokešová et al., 2015	...: Spatial rearrangement of runoff-generating ...	Science of the total environment	Nowadays, rapid growths of urban areas and associated land use/land cover (LULC)...	11
Review	Scopus	Guo et al., 2017	Achievements and Preliminary Analysis on China National Flash Flood Disasters Investigation and Evaluation	Journal of geo-information science	National Flash Flood Disasters Investigation and Evaluation project is ...	23
Letter	WOS	Schumacher and Herman, 2021	Reply to "Comments on 'Flash Flood ...'"	Journal of hydrometeorology	We applaud Gourley ...	3
Conference Paper	Scopus	Minea et al., 2017	*Identification of the potential flash floods risk areas in Romania using physiographic method*	International multidisciplinary scientific geoconference surveying geology and mining ecology management, SGEM	In recent decades the increase of the frequency of flash-flood conditions requires a correct identification of ...	1
...	...	...	...	...	...	...

This article comprehensively uses bibliometric analysis tools such as Microsoft 365, EndNote, Origin, VOSviewer, Citespace, etc. for literature feature analysis, co-word analysis, and cluster analysis. Firstly, use Microsoft 365 to organize literature data in a unified format and establish a literature database in conjunction with EndNote. In addition, EndNote is also used for literature storage, reading, and auxiliary citation of references; Then, use Origin for statistical calculations and draw a distribution map of literature features. Next, use VOSviewer to draw a graph of the cooperation between the author and the country. Finally, use Citespace to create a keyword clustering map.

3 Bibliometric analysis results

3.1 Distribution of publication volume

First, document characteristics analysis was made for 1,424 documents using the self-installed results analysis and retrieval function of WOS and Scopus. Then, the latest version of Excel in Microsoft 365 and Origin 2019 software were used to calculate and draw the statistical diagram, as shown in Fig. 3.



NO.	Paper type	Articles
1	Article; Proceedings Paper	1244
2	Conference paper	94
3	Review	40
4	Conference review	7
5	Book chapter	36
6	Letter	2

Figure 3. Number of publications: y is the number of publications, x is the year, the orange bar represents the number of publications, the light blue dashed line represents the trend of fitting the number of publications, and $y = 2E\text{-}130e^{0.1503x}$ is the formula corresponding to the trend of fitting the number of publications, R^2 is the coefficient of determination.

One conclusion was that the research in this field has shown exponential growth. Judging from the trend line that shows the predicted trend of documents published in the next four years, many documents will still be published in this field in the next few years. Another conclusion was that only 40 review documents were still very limited and accounted for only 2.8% of the sample database. Table 2 clearly shows that 2 of the top 10 highly cited documents closely related to this paper were review documents, accounting for 20 % of the top 10 highly cited documents, showing that there is a great demand for review documents, but the total number of such papers is very few, therefore the review of papers should be strengthened.

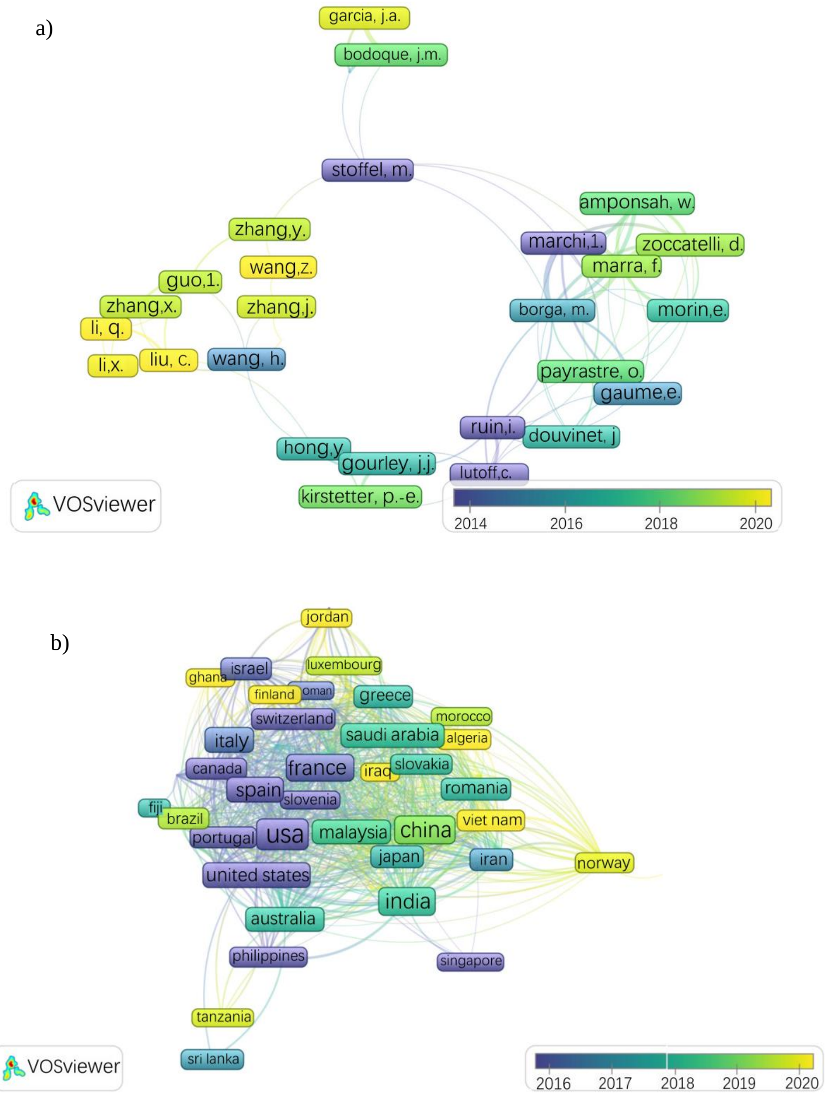
Table 2

Highly cited literature (TOP 10).

NO.	Cite Frequency	References	Document type	Research contents
1	738 (WOS) 761 (Scopus)	Prein, et al., 2015	Review	Convection-permitting mod-Els (CMP) is the main source of errors and uncertainties in large-scale models (LSM), and this review provides a common foundation for the CPM climate simulation theme
2	418 (WOS) 444 (Scopus)	Marchi et al., 2010	Article	Summarized the characteristics of past flash floods, established methods for archival and statistical data, and described the characteristics of flash floods from the perspectives of climate and basin morphology
3	386 (WOS) 427 (Scopus)	Khosravi et al., 2018	Article	Proving that machine learning can quickly identify disaster-prone areas in advance, four decision tree-based machine learning models were tested, and the results showed that alternating decision trees(ADT) have the strongest decision-making ability
4	301 (WOS) 312 (Scopus)	Merz and Bloschl 2003	Article	Propose a causal mechanism framework for identifying flood process types, examine feasibility through a large number of events and catchment areas, and analyze the statistical characteristics of each event type
5	273 (WOS) 293 (Scopus)	Borga et al., 2014	Article	Developing rainfall estimation and proximity forecasting plans, consolidating datasets, and integrating methods
6	267 (WOS) 296 (Scopus)	Youssef et al. 2011	Article	Using morphological analysis to estimate the flood risk level within a sub basin
7	162 (WOS) 182 (Scopus)	Islam et al. 2021	Article	Two hybrid ensemble models were applied and evaluated, demonstrating the ability to use advanced machine learning models for early identification of flash flood prone points
8	136 (WOS) 142 (Scopus)	Hampton et al. 2007	Review	Summarized the sheet flow process and explored the possibility of controlling its origin.
9	130 (WOS) 134 (Scopus)	Blöschl et al. 2008	Article	A distributed model was proposed to predict mountain torrents, and the problems encountered in modeling and modeling strategies were discussed
10	126 (WOS) 133（Scopus)	Špitalar et al. 2014	Article	Adopting interdisciplinary sociohydrological analysis of historical flash floods, the analytical framework for analyzing flash flood data and several factors affecting humans were discussed

3.2 Cooperation situation

VOSviewer 1.6.16 was adopted for the scientometric analysis , helping to discover key researchers and countries. Fig. 4 shows the co-word network diagram of the authors and the countries or regions. Fig. 4 (a) and 4 (b) show the spatial distribution of the authors and the countries or regions, and the color of the legend below represents the time when the paper was published. It can be seen that over the past 40 years, compared with the cooperation between countries, the distribution of authors is more discrete, and the connections between nodes are not close. Wang, z., Li, q., Liu, c., et al. are relatively active authors in recent years, while Jordan, Finland, Tanzania, and others are countries that have emerged in this field in recent years. Therefore, the research they carried out can be further followed up in the future. Fig. 4 (c) and 4 (d) show the authors' and countries' research heat maps, representing the strength of influence. It is not difficult to find that in Fig. 4 (c), authors Bodoque, j.m., Zhang, x., Borga, m., etc. are more influential authors, especially Borga, m., a highly cited author in Table 1. In Fig. 4 (d), USA, France, China, and India are the most influential countries.



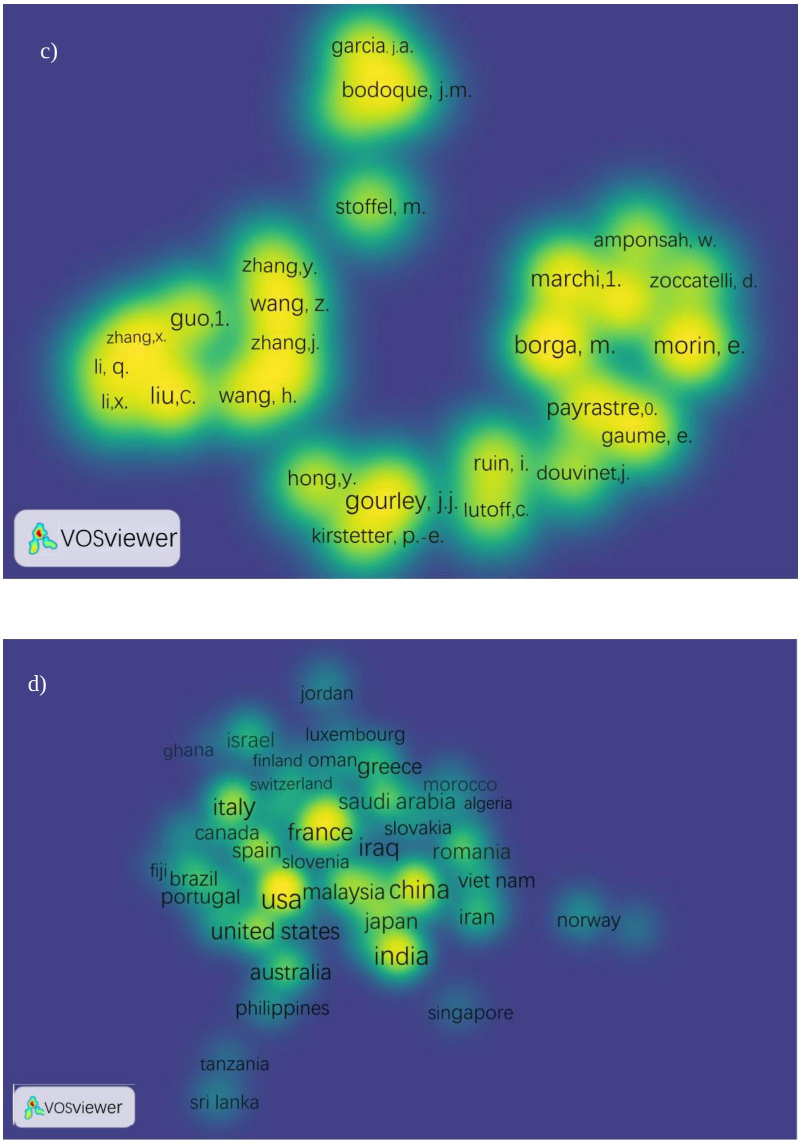


Figure 4. Visual network co-word analysis: a) author distribution label view, b) country or region distribution label view, c) author thermal diagram, d) country or region thermal diagram.

3.3 Research topic clustering results

CiteSpace R6.2.4 was used for cluster analysis, and 34 clusters were obtained. The network modularity of the cluster Q=0.4591>0.3 indicates that each cluster's network correlation structure is more prominent. Fig. 5 shows the first 11 clusters, of which #0 (weather forecasting) is the largest cluster. This is because short-duration heavy rainfall triggers flash floods and can provide a powerful driving force and rapid and strong water supply. The terms and documents involved in the cluster #9 (sediment transport) are most closely related to the research contents of this paper, and the keywords are enlarged and displayed in the circle on the right side of Fig. 5. It can be intuitively found that the keywords of “rivers” and “sediment transport” are most prominent, showing that the evolution law of sediment transport in the rivers is the content of the cluster that has the longest research history and is most important.

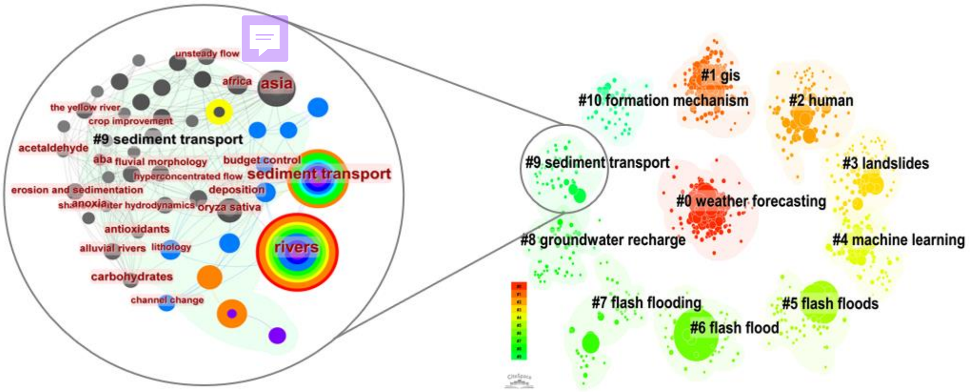


Figure 5. Research topic clustering results.

The cluster details were sorted by the number of co-cited publications, as shown in Table 3. The cluster #9 has the highest Silhouette value, indicating that the cluster has the best structure and more reasonable internal similarity. The top five terms were listed in the table. It is obvious that “bedload transport”, “desert”, “grain size” and “dynamics” are the key research contents of cluster #9.

Table 3

Clustering of literature co-citation profiles.

Cluster ID	Size	Silhouette	Mean （year）	LLR-based TOP5 term
0	178	0.61	2010	flash flood; soil water content; headwater catchment; tracking algorithm; watershed
1	139	0.572	2013	flash flood; water conveyance system; southern italy; flow-like landslide; predicting property
2	86	0.795	2008	flooding; floods; article; disaster; human
3	78	0.732	2005	flash flood; hengduan mountains; spatiotemporal variation; heavy rainfall; risk assessment
4	77	0.797	2012	flash flood; ANN; SVM; RF; deep learning
5	76	0.881	2002	flash flood; floods; flooding; backwater; romania

6	58	0.83	2000	flash flood; mini disk tension infiltrometers; soil infiltration; hydrologic scaling
7	52	0.921	1992	geomorphology; hydrology; flow of water; water levels; statistical methods
8	51	0.901	1996	drylands; fractional exponential decay; precipitation; acacia pachyceras; arava valley
9	46	0.943	2007	sediment transport; bedload transport; desert; grain size; dynamics
10	39	0.869	2009	geomorphology; hydrology; frequency analysis; return period; water levels

4 Research practice on flash floods considering sediment effects

Through the previous bibliometric analysis, we have learned that the research on disasters caused by the joint action of water and sediment is one of the important directions in this field. Therefore, this section focuses on exploratory research from the perspective of “water-sediment”, devoted to establishing an early identification model of a flash flood, water and sediment disaster-prone areas based on data-driven and water-sediment dynamics by revealing the flash flood and sediment coupled disaster-causing mechanism, and analyzes several sources of uncertainty affecting the evaluation results.

4.1 Mechanisms

Based on the documents and survey results (Li et al., 2022b), flash flood and sediment disasters usually occur in steep-gentle transition reach (Li et al., 2022a), tributary confluence reach (Li et al., 2022), curved reach (Yuan et al., 2022), and bridge and culvert reach (Li et al., 2022c), which are mainly manifested in various disaster-causing modes such as the sharp rise of water level due to sediment deposition, river diversion and bridge and culvert clogging.

The disaster-causing mechanism of flash floods and sediment disasters shows that the flood carries great loads of sediment downstream, which leads to the sharp adjustment of the gully bed and the rise of the water level, thus causing disasters. In Fig. 6 (a), when the flash flood carries large amounts of sediment to move to the steep-to-gentle gully section, loads of coarse sediment are deposited to drive the rapid uplift of the riverbed. When the sediment in the flash flood gully flows into the next river channel, the sedimentation and the sharp rise of the water level will occur in the confluence area, causing disasters, as shown in Fig. 6 (b). When the sediment moves to the gentle slope curved section of the gully, the sediment will deposit, which could easily induce river diversion and cause disasters, as shown in Fig. 6 (c). Suppose water-blocking facilities such as cross-ditch bridges and culverts are in the gully. In that case, the rise of the local water level will result in decreased flow velocity, reduced sediment-carrying capacity of flow, culvert clogging due to sediment deposit, raised water level or induced river diversion, thus causing disasters, as shown in Fig.6 (d).

Figure 6. The frequent occurrence of mountain flood, water and sand coupling disasters in Sichuan Province, China, based on the national historical flash flood disaster database, on-site research on typical mountain flood, water and sand disasters, and model experiments, it was found that flash flood and sand disasters usually occur in these areas: a) steep and gently connected river sections, b) tributary and confluence river sections, c) curved river sections, d) bridge and culvert river sections (photo taken by author).

Based on field investigation (Hu et al., 2022), laboratory tests (Zhou et al., 2021b) and theoretical analysis (Zhou et al., 2021a), researchers have analyzed the change of scouring and siltation in the river channel caused by the change of water and sediment conditions. Li et al. (2021b) discovered that the chain characteristics of flash flood and sediment disasters can be summarized as orderly predictability of chain nodes, amplification of water and sediment variation disasters and coupling of disaster-causing factors at the watershed scale. The details are as follows:

- Orderly predictability of chain nodes

In the chain of rainstorms, flash floods and sediment disasters, according to the time development process and the influence of the spatial combination of disaster-causing factors, the chain nodes such as weather situation, rainfall distribution, topography, river system, water and sediment process, submergence, loss and disaster impact are orderly and predictable.

- Amplification of water and sediment variation disasters

Rainstorms, flash floods and sediment disasters are orderly and predictable. However, in the actual rainstorm and flash flood process, due to the special distribution and coupling of various wading structures, sediments, and disaster-bearing bodies in the watershed, there will be abnormal variations in sediment yield and runoff generation, which is caused by the bridge and culvert blocking or outburst, the sediment erosion and deposition and the combined effects of various factors. Also, serious disasters may occur even if the rainfall is relatively common. Therefore, the variation of water and sediment has obvious disaster amplification effects.

- Coupling of disaster-causing factors at the watershed scale

As a triggering factor, with strong kinetic energy, the rainstorms in mountainous regions can make the material and energy in the watershed increase sharply in a short time, destroying the watershed's equilibrium state before rain (Ye et al., 2021). Different disasters will occur if the flood submergence area is inhabited or equipped with disaster-bearing bodies such as transportation, communication, factories and mines, enterprises, etc. Regarding the occurrence process, water and sediment disasters have nodes such as weather situation, rainfall distribution, topography, river system, water and sediment process, submergence and loss, etc (Li et al., 2023). However, the chain characteristics of water and sediment disasters reflect that various disaster-causing factors are coupled at the watershed scale (Liu et al., 2021; Ran et al., 2022). For the intersection of the gullies, the coupling of disaster-causing factors in the higher-level watersheds of water and sediment deposits should be provided as well.

4.2 Early identification models

The factors of flash flood and sediment coupling include rainfall and topography, river dynamics-related factors such as river channel type and sediment movement. The traditional method of predicting the evolution of flash floods based on hydrological models may misestimate the degree of disaster or underestimate the risk of disaster when rainstorms and flash floods occur. In particular, it cannot effectively identify and predict the “small floods and big disasters” caused by the uplift of the river channel. To solve the problem of wide distribution and strong concealment of flash flood disasters, we proposed early identification methods for flash flood and sediment disaster-prone areas at the regional and reach scales, respectively.

4.2.1 Data-driven based intelligent model

Due to a lack of consideration of sediment factors, the traditional data-driven identification methods for flash flood disaster-prone areas make it difficult to identify the flash flood and sediment disaster-prone areas induced by heavy rainfall and sediment deposits.

The fast and accurate acquisition of the spatial distribution and area of the landslide areas can provide important support for the early identification (Zhang et al., 2022). He et al. (2020) proposed a regional landslide extraction method. Bai et al. (2023) applied a landslide area extraction technology based on UAV image and deep learning to effectively combine deep learning in the computer field. Yuan et al. (2022) incorporated landslide deposits into the data-driven model as a deposit factor. They combined traditional flash flood disaster predictive factors such as topographic data, geological data, and hydrological data to construct a model of influencing factor contribution-ensemble learning coupling to obtain the data-driven early identification methods. The technical flowchart is shown in Fig. 7.

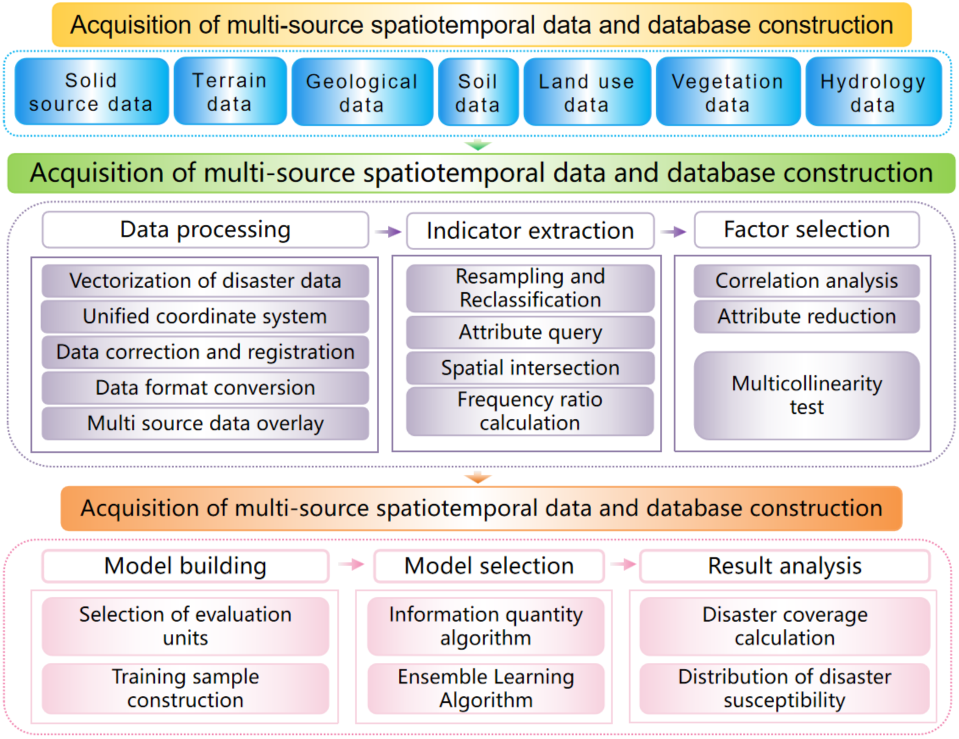
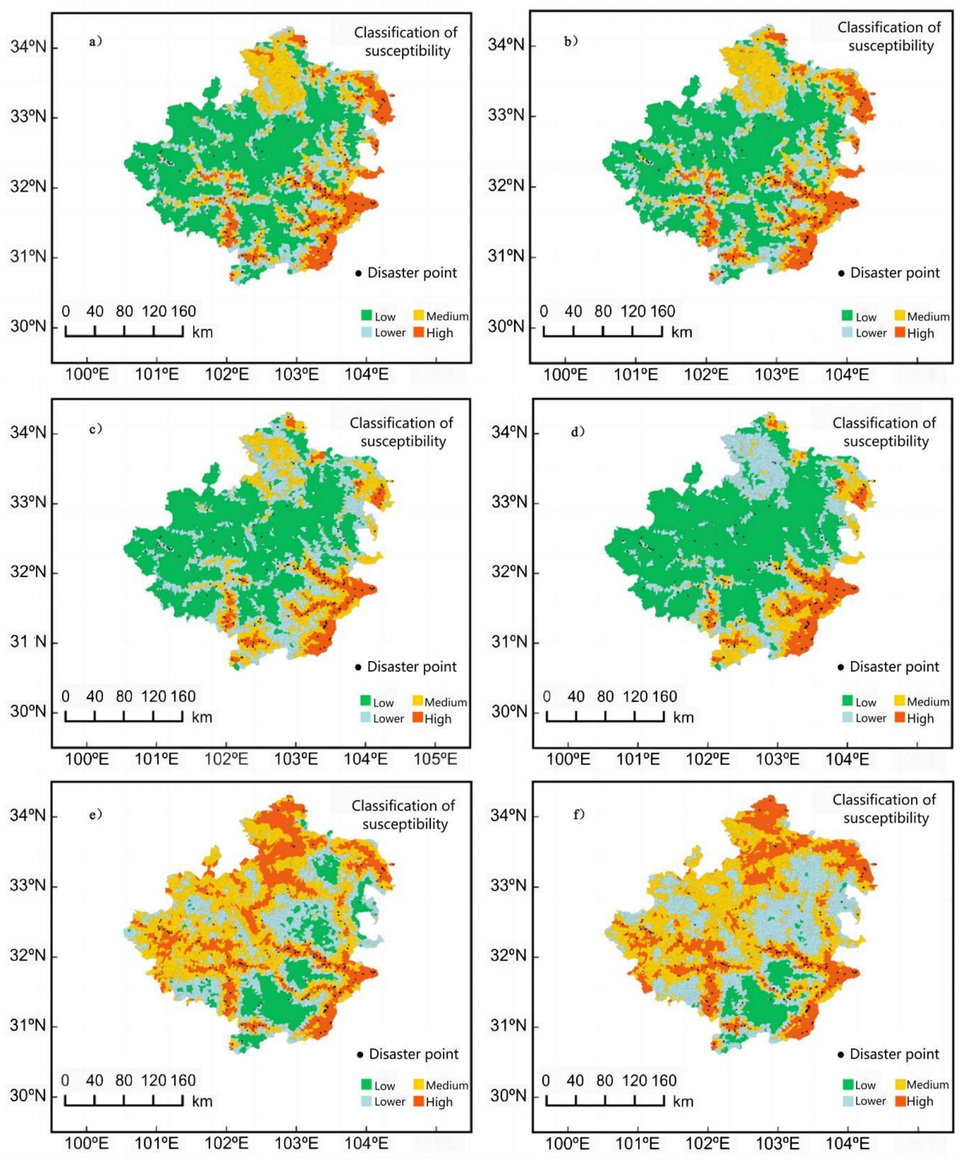


Figure 7. Data driven model technology flowchart.

The spatial superposition analysis was made for the spatial distribution of the frequency ratio of the positive and negative sample influencing factors in the research area. The frequency ratio, amount of information, and certainty coefficient of the influencing factors were output to the disaster susceptibility interval ([0, 1]) as the input item of two ensemble learning classification algorithms in the form of a one-dimensional vector through the ensemble learning classification algorithm tool in the MeteoInfo integration framework (Liu et al., 2022). By comparing output results and existing flash flood risk investigation and assessment results, the national flash flood risk investigation and assessment research (FFIA) has become a more recognized research result in the field. Taking FFIA as the reference object and the coverage rate of disasters in high-risk areas as the evaluation index, the results in Aba area were evaluated (Yuan et al., 2022), as shown in Fig. 8. The results are as follows:



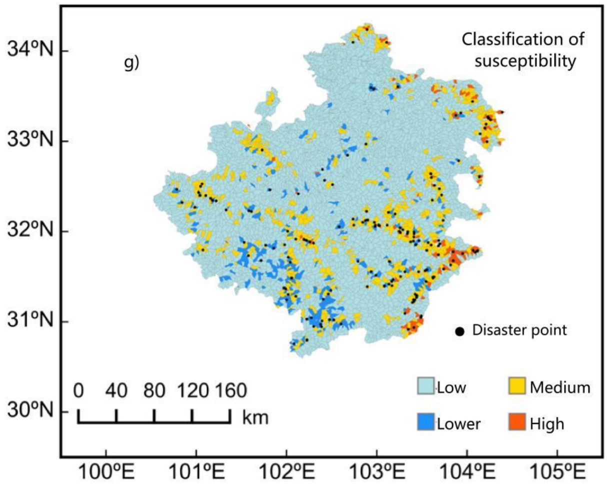


Figure 8. The identification results of this high-risk area: a) frequency ratio adaptive enhancement model, (b) frequency ratio random forest model, (c) information quantity adaptive enhancement model, (d) information quantity random forest model, (e) certainty coefficient adaptive enhancement model, (f) certainty coefficient random forest model, and (g) FFIA data.

Compared with the FFIA data, the coverage in high-prone areas increased by 23.2%-45.4% in the data-driven results. Specifically, the coverage rate of the frequency ratio-adaptive enhancement model in high-prone areas increased by 40.5% compared with the FFIA result; the coverage rate of the frequency ratio-random forest model in high-prone areas increased by 41.2% compared with the FFIA result; the coverage rate of the information amount-adaptive enhancement model in high-prone areas increased by 23.7% compared with the FFIA result; the coverage rate of the information amount-random forest model in high-prone areas increased by 23.2% compared with the FFIA result; the coverage rate of the certainty coefficient-adaptive enhancement model in high-prone areas increased by 42.7% compared with the FFIA result; the coverage rate of the certainty coefficient-random forest model in high-prone areas increased by 45.4% compared with the FFIA result.

4.2.2 Hydrodynamic model

Due to the complex topography and wide coverage of the mountainous watersheds

(Faisal et al., 2023), water-sediment dynamic models can be used to simulate the target object's water-sediment coupled movement to accurately identify the early disaster-prone areas (Imaizumi et al., 2008). Many scenarios need to be simulated in the early stage, including different conditions of rainfall, flow and sediment movement. However, the workload is huge and the cost of workforce and material resources is too high. Meanwhile, the rivers in mountainous areas have complex geometry (Lin et al., 2023), and flood-obstructing buildings such as steep-gentle transition reaches, tributary confluences, curved reaches, bridges and culverts are widely distributed, which can easily lead to spatial heterogeneity distribution (Deal et al., 2023). We have constructed a set of quantitative methods based on hydrodynamic methods propose the determination conditions of danger-hidden reaches such as steep-gentle transition reach, tributary confluence reach, curved reach, bridge and culvert reach.

- **Steep-gentle transition reach**

Under the condition of saturated sediment transport, if the sediment transport capacity of the upper reach is greater than that of the lower reach, it will lead to sedimentation in the lower reach, raise the riverbed, and sharply increase the water level. Moreover, it will reduce the gradient of the lower gully bed, further widen the sediment transport capacity gap between the upper and lower reaches, and result in more serious sedimentation and raised water levels. Flash flood and sediment disasters such as silting and submergence can easily occur during this process. For the steep-gentle transition reaches, due to the different riverbed gradients, the bed load transport rate will change near the transition reach. The sediment transport-gradient empirical formula of the steep-gentle transition reach is as follows:

$$\frac{g_{s1}}{g_{s2}} \sim \left(\frac{S_1}{S_2}\right)^{3/2} \tag{1}$$

Where g_s is the saturated bed load transport rate, S is the bed gradient, Subscript 1 is the upper reach and Subscript 2 is the lower reach.

- **Tributary confluence reach**

In the tributary confluence of the mountainous rivers, affected by the characteristics of incoming water and sediment of the major tributary, the disaster is mainly due to the mutual backwatering between main stream and tributary and the large gradient of tributaries. If the water flow meets in the confluence, the upper reach forms the backwater area, the lower reach forms the flow separation area, which is easy to cause sediment deposition. Meanwhile, the cross-section of the river is reduced, and the conveyance capacity is reduced. The large tributary gradient and excessive incoming sediment will also lead to siltation and submergence in the confluence area, thus inducing major flash floods and sediment disasters. The momentum expression formula of the tributary confluence reach based on river width and gradient was proposed as follows:

$$\frac{M_1}{M_2} = \frac{B_1}{B_2}\frac{J_1}{J_2} \tag{2}$$

Where M is the water flow momentum, *B* is the river width, *J* is the gradient, Subscript 1 is the tributary, and Subscript 2 is the main stream.

- **Curved reach**

The mechanism of disasters in the curved reach is multifaceted (Yuan et al., 2021). First, the tortuous river channel and the unevenly distributed water velocity are easy to form high-velocity and low-velocity flow areas, resulting in the local intensification of flood disasters. Then, the curvature of the river channel and the inertia effect of the fluid will lead to streamlined bending and twisting, and whirlpools and vortexes, and further raise the local water level of the river channel to form clogging and poor flood discharge. In addition, the curvature of the river channel will also affect the transport of sediment and result in sedimentation, inadequate dredging and narrowing of the river channel, thus affecting the river channel's carrying capacity and drainage capacity and increasing the risk of flood disasters. We have found that the ratio of the disaster-causing water depth between the curved reach and the lower reach should meet Formula (3), that is, whether it is a criterion for determining the flash flood disaster-prone areas:

$$\frac{h_1}{h_2} = \left(\frac{B_2}{B_1}\right)^{3/5}\left(\frac{J_2}{J_1}\right)^{3/10} \geq \frac{h_{1\mathrm{beach}}+h_0}{h_{1\mathrm{beach}}} \tag{3}$$

Where B is the average river width, J is the riverbed gradient, $h_{1\mathrm{beach}}$ is the flood land line water level when the curved reach is submerged and h0 is the water depth required for disaster prevention.

- **Bridge and culvert reach**

Bridges and culverts are often built on the gullies of the mountainous rivers for local residents to pass through. However, due to the simple structure and low building standards (low flood control standards), these bridges and culverts play a role in obstructing floods when flash floods occur. In recent years, it has been found that clogging occurs when coarse sediments and floating woods pass through these low-standard bridges and culverts (Brussee Anneroos et al., 2021). Therefore, building low-standard bridges and culverts is also an important factor in early disaster identification. In the process of identification, if it is found that the bridge and culvert foundations occupy the conveyance channel of the gully, it is determined as a disaster-prone area.

We applied the method based on hydrodynamic methods to the risk identification in Aba Prefecture, drew the flash flood disaster point distribution map of Aba Prefecture via ArcGIS and set the FFIA results as the base map for comparison, as shown in Fig. 9. Taking the coverage rate of disasters in high-risk areas as the evaluation index, the disaster coverage rate in the results of FFIA was 16.5%. Compared with the results of FFIA, the methods increased by 52.3%. Many flash flood disasters in low and medium risk areas were successfully identified.

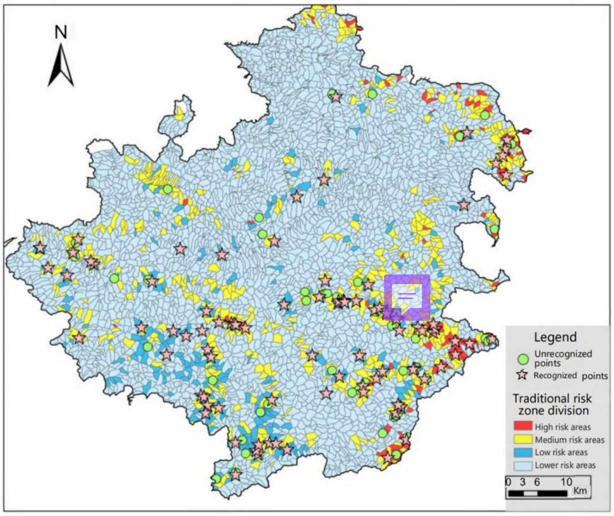


Figure 9. Comparison of research results based on hydrodynamic methods and national flash flood risk investigation and assessment.

4.3 Uncertainties

Previous studies have shown that the uncertainties of influencing factors, multi-source spatiotemporal data, models, and evaluation units will affect the reliability and accuracy of the evaluation results, as shown in Table 4. This section analyzes the sources of uncertainty based on the model evaluation results, and the details are as follows.

Table 4

Typical cases that have an impact on evaluation results.

No.	Influencing factors	Case Studies	Description
1	Uncertainty of influencing factors	Zhang et al., 2022	Heavy rainfall is the main driving factor for triggering flash floods

2	Uncertainty of multi-source spatiotemporal data	Emery et al., 2016	The evaluation results of the model largely depend on the selected parameters and influence range, and different data may lead to different sensitivity indices
3	model uncertainty	Majhi et al., 2022	The uncertainty of Global Climate Model(GCM) is the most sensitive to regional rainfall characteristics, followed by elevation
4	Uncertainty of evaluation units	Lee et al., 2004	Using a GIS data platform to evaluate the impact of evaluation units on prediction results
...	...	...	...

4.3.1 Uncertainty of influencing factors

Typical flash flood disaster events have shown the characteristics of high coupling of various disaster-causing factors (Špitalar et al., 2012). Therefore, the in-depth analysis of the uncertainty of early identification and influencing factors of flash floods is of great significance for improving the identification accuracy. There is still no unified view on the causes of flash flood and sediment disasters due to the complexity of the environment and the different development stages. We developed a method to predict the uncertainty of “rainfall process-flood process-water and sediment coupling process” stage by stage, studied the relationship between rainfall and sediment transport rate under different rainfall conditions to identify rainfall patterns, and compared the relationship between the evaluation factors of FSDS (Flood and Sediment Disasters Susceptibility) and the disasters fitted by different algorithms to draw maps by the most reasonable and efficient methods. To improve the accuracy of early identification, it is recommended to consider the evaluation factors related to the occurrence of disasters as much as possible and adopt multi-source data obtained from multiple channels for analysis.

4.3.2 Uncertainty of multi-source spatiotemporal data

The data involved of flash flood disasters include real-time rainfall, soil water content, field investigation, disaster analysis and evaluation, prediction model, early warning model, document data, etc. (AL-Areeq et al., 2023). These data have strong multi-source heterogeneity and highly dynamic spatiotemporal characteristics, which challenges disaster data collection, storage, and calculation (Li et al., 2022). In investigating and studying early flash flood and sediment disasters, researchers conducted on-the-spot investigations on the disaster occurrence sites to obtain geological, topographic, and geomorphological factors. They completed early identification under the condition of early multi-source data according to the geological and topographical maps. Chen et al. (2021) realized the raw data acquisition of sensors and various sources and carried out preprocessing such as storage, cleaning, conversion, and dimension reduction to construct the associated database. Currently, the data is mainly acquired through the field investigation of researchers (Siebert et al., 2016) and the measurement of relevant information on the disaster areas by satellite remote sensing (He et al., 2020). The topographical map, vegetation coverage, rainfall, and other related data can be obtained through the above measurement methods to constitute a data set for early identification. Establishing a deep learning sample database and verifying deep learning automatic interpretation accuracy can provide data guarantee. We conducted spatial analysis and integrated multi-source data based on the GIS platform to form basic data for early identification. Since different methods and means measure multi-source data and have differences in format, spatial resolution, coordinate system, etc., it is suggested that the basic data should be unified to the same standard before being used in the early model construction.

4.3.3 Uncertainty of models

In addition to the uncertain influencing factors and multi-source spatio-temporal data, inconsistent input parameters, inaccurate initialization, and uncertain model structures will all lead to the uncertainty of early identification models (Jafarzadegan et al., 2021). In view of the strong uncertainty, further research and reliability evaluation of the models are needed to reduce the uncertainty of the model results (Abbaszadeh et al., 2021). It is particularly important to carefully select the identification models in the calculation process. Under equal identification accuracy, different models will have other distribution characteristics. Therefore, it is still difficult to conclude which identification model is more conducive to modeling. Previous studies have shown that compared with a single model, based on balancing the model identification accuracy and computational burden as much as possible, various coupling models (Ahmadisharaf et al., 2018), integrated models (Tehrany et al., 2014) and hybrid models (Moftakhari et al., 2019) have more advantages in model fitting and prediction performance.

4.3.4 Uncertainty of evaluation units

The reasonable selection of evaluation units is very important to reduce the uncertainty of evaluation units. In previous studies, the grid unit was directly used as the evaluation unit. Different susceptibility zones were often divided in a single watershed, but the integrity of disaster occurrence was ignored, which is inconsistent with the actual environment and not conducive to accurately identifying flash flood disasters (Sun et al., 2019; Duan et al., 2022). To solve the zone differences in a single watershed, we divided the susceptibility results calculated by the grid units in the form of watershed units, took the average value of susceptibility in each sub-watershed as the unit value of the sub-watershed in the research area, and divided it into four levels by natural discontinuity methods to obtain the susceptibility classification of flash flood and sediment disasters based on watershed units.

5 Discussion

5.1 The potential of bibliometric methods

Based on the previous bibliometric analysis, this paper further analyzes the evolution law of keywords in this field. It applies Citespace to obtain the time zone map of the evolution law of the main keywords related to the “sediment transport” over time. Fig. 10 reflects the evolution of flash flood and sediment transport research from sporadic research in hydrology (flash floods and floods) in 1981 to intensive research in natural disasters (debris flows, erosion, infiltration, etc.) after 1990. Subsequently, the research shifts its focus to underlying surface correlations (e.g., digital elevation model, lithology) and then to the characteristics of the river channel (e.g., bank erosion, rivers, fluvial morphology, etc.). Through these evolution processes, it is not difficult to find that the field is gradually paid attention to the impact of sediment and shifted the previous focus from the single research to the integrated research of multiple disciplines and from the influence of single factors to the comprehensive influence of multiple factors.

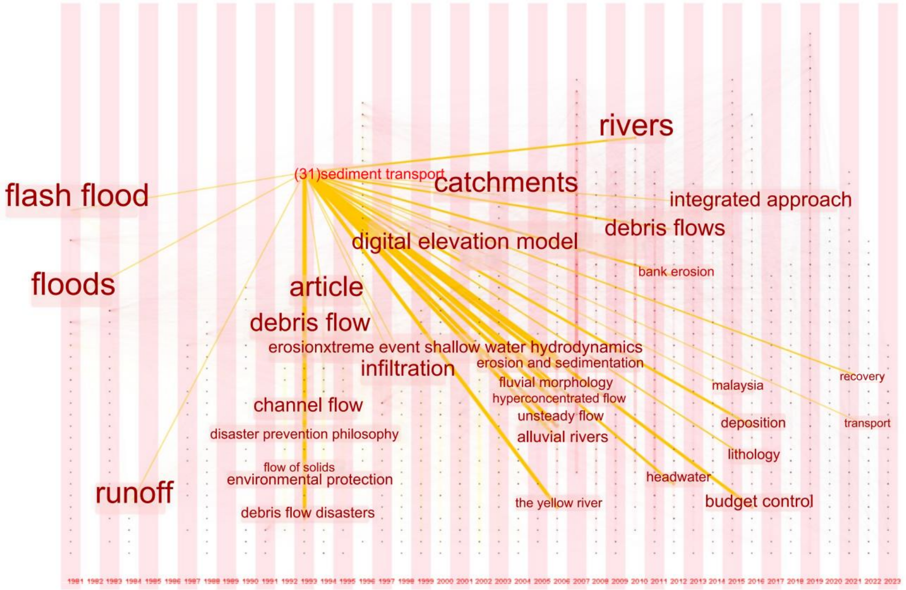


Figure 10. Research time zone map: the red five pointed star marks the theme keyword "sediment transport", and the lines connect the related keywords. The thicker the lines, the closer the connection

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between the keyword and "sediment transport". The size of the keyword font on the graph represents the frequency of occurrence, and the more frequent the occurrence, the more font the keyword has. .

In addition, due to the difficulty of processing mass data, this study only considers peer-reviewed papers, but not other materials in this field, such as government reports, news reports, webpage information, and other non-academic documents. Meanwhile, the initially set keywords may not cover all articles in the field, and measurement software can only be used to identify important nodes, which may ignore some valuable documents. Therefore, the document sample database needs to be constantly updated in future research to conduct more extensive and in-depth research.

5.2 Research on Expanding Wide and Narrow River Sections

Documents show that the research on the disaster-causing mechanism of flash floods has gradually developed from qualitative analysis to quantitative analysis (Chen et al., 2020; Ding et al., 2023; Chen et al., 2023). However, the field still need to be studied thoroughly and continuously to enhance the understanding of the water and sediment coupled disaster-causing law. For example, the research on the coupled disaster-causing mechanism of water and sediment in wide and narrow rivers must be expanded. Due to the influence of hydrological characteristics, geological structure, and other factors, the river is generally characterized by a plane shape consisting of a narrowed valley section and a widened non-valley section. The wide and narrow river channel is the most common river pattern in mountainous rivers. The narrowed section of the river channel usually has an obvious bayonet effect. The restricted section in the non-flood period is characterized by the drop, with shallow water depth, large flow velocity (Yan et al., 2022). The drop effect of the narrowed section in the flood period should be weakened, the flow velocity should be slowed down, and the sediment transport rate should be greatly reduced. We verified the water level along the research reach in the laboratory test (Yan et al., 2021). The preliminary findings show that in the wide and narrow river channel, a large amount of sediment from the upper reach will cause sedimentation in the widened section and scouring in the narrowed section, forming typical shoal and step-pool bed forms and uplifting the riverbed. It can be seen that the change in river width is one of the key factors affecting flood discharge in mountainous rivers, and the mechanism research of this kind of reach should be strengthened in the future.

5.3. Early identification model based on knowledge graph

In summary, the early identification models of flash floods mainly include hydrological information-based models (Guo et al., 2022), data-driven models (Ge et al., 2023), hydrodynamics-based models (Bonnifait et al., 2002), knowledge mapping-based models (Chen et al., 2023), etc. Among them, the knowledge mapping-based model is a relatively cutting-edge model that has recently attracted much attention in geoscience (Zhang et al., 2022). The mapping refers to the atlas compiled by type, including pictures or photos, text descriptions, etc. (Paulheim et al., 2017), a form to better understand things by describing images and texts. Knowledge mapping is an identification method that forms knowledge discovery by aggregating various information(Ma et al., 2021). Chen et al. (2020) used knowledge mapping to construct the landslide semantic network, showing that the model can make an effective prediction in the case of small amounts of data. Zhang et al. (2023) presented the types and characteristics of regional fluvial facies in the form of knowledge mapping to construct the knowledge system of fluvial facies. Xu et al. (2023) systematically combed the technical methods and processes of constructing landslide knowledge mapping. They proposed that the process of constructing landslide knowledge mapping can be extended to other types of disasters.

The knowledge mapping for early identification of flash flood disasters requires both pictures and texts, that is, it can not only clearly understand the evolution process and corresponding characteristics of flash floods according to the pictures but also accurately identify them according to the text descriptions. At present, although the construction of knowledge mapping, especially for flash flood, is still blank, we can try to analyze it in combination with several other models in future research and propose a more scientific fusion model to provide new ideas for the construction of early identification models. Recently, we have simplified and concluded the three aspects of disaster-causing factors, disaster-causing reasons and damage modes and summarized eight typical disaster-causing modes of water and sediment disasters as follows: rainstorm-flood-flooding mode, rainstorm-flood-blocking-backwatering mode, rainstorm-flood-outburst-flooding mode, rainstorm-flood-upper outburst and lower blocking-backwatering mode, rainstorm-flood-sediment deposition-flooding mode, rainstorm-flood-sediment deposition-diversion-flooding mode, rainstorm-flood-sediment deposition-submergence mode and rainstorm-flood-upper outburst and lower blocking-sediment deposition-backwatering mode (Table 5). In the future, we will consider preparing each typical disaster-causing mode into knowledge mapping and specify the identification criteria to distinguish the types of flash flood disasters intuitively and conveniently.

Table 5 Typical disaster mode.

No.	Mode name	Disaster causing factors	Characteristics of water and sediment anomalies	Hazard mode
1	Rainstorm-flood -flood model	Rainstorm, flood	Runoff surge caused by rainstorm	Flood inundation
2	Rainstorm-flood-blockage- flood model	Rainstorm, flood, river blockage	Runoff surge caused by rainstorm, rapid rise of water level due to backwater	Flood inundation
3	Rainstorm-flood-break -flood model	Rainstorm, flood, collapse of water retaining structures	Collapse leading to a surge in runoff	Flood impact, flushing and flooding
4	Rainstorm-flood-upper burst lower blockage-overflow model	Rainstorm, flood, collapse of water retaining structures river blockage	Collapse leading to a surge in runoff	Flood impact, inundation
5	Rainstorm-flood-sediment deposition-overflow model	Rainstorm, flood, sediment	Coupling of water and sediment leads to a surge in runoff	Water and sand flushing and flooding
6	Rainstorm-flood-sediment deposition-diversion -inundation model	Rainstorm, flood, sediment	Channel siltation and filling, diversion of water flow	Water and sand flushing and flooding
7	Rainstorm-flood-sediment deposition-submergence model	Rainstorm, flood, sediment	Runoff surge caused by rainstorm, sediment scouring and silting	Water and sand flushing and flooding, cover with silt
8	Rainstorm-flood-upward collapse and downward blockage-sedimentation-overflow mode	Rainstorm, flood, sediment, collapse of water retaining structures, river blockage	Collapse leading to a surge in runoff, sediment scouring and silting	Water sand impact, flushing and flooding、Inundation

5.4. Reduce model uncertainty

Although many scholars have researched and discussed the uncertainty of flash flood disasters, such as random set theory, fuzzy set theory, possibility theory, etc., these methods and theories have certain limitations. The complex of flash flood, uncertain models, and diversified influencing factors, etc., make the accuracy of early identification difficult to meet the needs, and there is a lack of the theories and methods of quantitative combination. For example, it is a challenge to establish the criteria for determining typical disaster-prone reaches. At present, the parameters in the empirical formula still need to be optimized. In the future model construction process, it is necessary to consider the uncertainty of parameters and structures, such as underlying surface conditions and fully integrate multi-source spatiotemporal data to improve the model's reliability and identification accuracy.

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6 Conclusions

The development of the field can not only effectively predict and warn in advance, reduce casualties and property losses, but also provide scientific basis and favorable support for flash floods' prevention and control strategies. Given the suddenness, complexity, difference, and uncertainty of flash flood disasters, this paper summarizes the results in the field of early identification of flash floods based on bibliometric analysis and research practice and lists as follows:

(1) Bibliometrics: as a very active research field, it has attracted more and more attention from the academic circle in the past 40 years, and the number of documents published will continue to show an exponential upward trend in the future; the review papers are cited more times, but the total number of citations is too small to meet the demand, so the intensity of document review and research should be strengthened; the cooperation between authors is less, the author cluster is not obvious, but there is relatively more cooperation between countries; weather forecasting is the largest cluster, and keywords considering sediment factors also form a cluster, but the number of papers published is scarce.

(2) Water and sediment coupled disaster-causing mechanism: flash flood and sediment disasters usually occur in locations such as steep-gentle transition reach, curved reach, tributary confluence reach, bridge, and culvert reach; flash flood and sediment disasters have three chain characteristics, that is, orderly predictability of chain nodes, amplification of water and sediment variation disasters and coupling of disaster-causing factors at the watershed scale.

(3) Early identification model of flash floods: the deposits identified by remote sensing methods are incorporated into the data-driven intelligent model as a deposit factor. For sediment-laden watersheds, the model can improve the identification coverage of disaster-prone areas compared with the traditional models. Meanwhile, the hydrodynamic model suitable for the river scale is proposed, and the main controlling factors for sediment deposition and uplift in typical reaches are discovered based on the theoretical analysis of water and sediment dynamic processes in distinct reaches.

(4) Flash flood uncertainty: the influence of uncertainty reduction on the field is summarized from five aspects: influencing factors, data, models, evaluation units, and evaluation results. Carefully considering the influence of various uncertainties is the key to improving identification accuracy.

In conclusion, the research on the field is still in its infancy, and there are still a lot of gaps that urgently need to be studied. This paper enriches the document sample database, summarizes the research progress in this field, reveals the flash flood and sediment coupled disaster-causing mechanism, establishes early identification methods based on data-driven and water-sand dynamics, and analyzes the uncertainty sources of the model evaluation results and the suggestions for improving identification accuracy, so as to provide some reference for the early identification of flash flood disasters in the future.

Data availability. No data sets were used in this article.

Author contributions. All authors contributed to the conceptualization of the paper and its contents. Heng Lu and Chao Liu developed the structureof the paper. Zhengli Yang wrote the paper, produced all figures and tables,and formatted the article. Kai Song, Zhijie Zhang, and Lei Ma produced the visualizations. Heng Lu, Ruihua Nie, Wanchang Zhang, and Chen Chen reviewed, revised, and supervised the progress of the paper. Min Zhang, and Gang Fan contributed to the conceptualization of ideas and to the writing and editing of the manuscript.

Competing interests. The contact author has declared that none of the authors has any competing interests.

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