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Review article

A review of the flood management: from flood control to flood resilience

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ABSTRACT

Climate change and socioeconomic developments are increasing the frequency and severity of floods. Flood management is widely recognized as an effective way to reduce the adverse consequences, and a more resilient and sustainable flood management approach has been the goal in recent studies. This study used a detailed bibliometric analysis of keywords, terms and timelines in the research field of the flood research. It provides new insight into the flood research trends, by examining the research frontiers from 2000 to 2021. We conclude that the trend of flood research has experienced a transition from flood control to flood resilience. The review shows that flood research has moved from traditional flood management, which provides mitigation strategies, to flood risk management, which provides an adaptation approach—adjusting mitigation measures, to flood resilience management, which provides a more resilient and sustainable plan to cope with flood disasters. We also present a detailed overview of the field of flood research, and review the definition of risk, risk analysis methods, flood management, flood risk management, flood resilience, and corresponding implementation strategies. We conclude that integrating the concept of resilience into the framework of risk management is a better approach in future flood management directions. Consequently, appropriate options and decisions prior to disaster, during disaster, and post-disaster will effectively reduce the adverse consequences using the theory of risk, resilience, and sustainability.

1. Introduction

Disastrous floods driven by rapid urbanization and extreme weather events have caused millions of fatalities, and continue to cause tens of billions of dollars of direct economic loss each year. And under the background of global warming, such losses will continue to increase in the future (Bloeschl et al., 2019; CRED and UNISDR, 2020; Hallegatte et al., 2013), as the intensity of extreme precipitation events increases (Tabari, 2020) and the population exposed to water-related disasters rises (Jongman et al., 2012; Paudel et al., 2014; Tellman et al., 2021). Worse still, river flooding, flash floods, urban floods, and coastal floods may occur simultaneously, resulting in serious compound flooding from extreme river flow, heavy rainfall, and storm surges (Ming et al., 2022). Identifying the areas at risk of river flooding, urban flooding, and coastal flooding is a complicated process, as the causes of these events differ. Although it is known that flood risk increases with climate change, population growth and the increase of economic assets, and that risk is dynamic, constantly changing with underlying surface condition changes (Hallegatte et al., 2013; Lai et al., 2020). Therefore, managing flooding to cope with increasing flood risk is urgent.

Previous research has shown the urgent need to deal with flood events (da Silva et al., 2020), and it is essential to develop future flood management strategies to reduce the adverse consequences and cope with more complex types of floods. Many countries have implemented a series of practices to manage storm water, flood disasters, etc. For example, green infrastructure (GI), low-impact development (LID) and best management practices (BMPs) have been implemented in the United States; sustainable urban drainage systems (SUDS) in the United Kingdom; water-sensitive urban design (WSUD) in Australia; and low-impact urban design and development programs (LIUDD) in New Zealand (Fletcher et al., 2014; Liu et al., 2017; Perhaps the most ambitious and far-reaching project has been the Delta Programme in the Netherlands, implemented

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between 2006 and 2015. This project aimed to create “room for rivers” as well as delivering some auxiliary benefits (Rijke et al., 2012; Van, 2016). It was developed to cope with increasingly serious flood disasters, is a more sustainable method than the Netherlands' traditional embankment measures, and has been successful in lowering the flood risk (Asselman and Klijn, 2016). The European Union defined the concept of nature-based solutions (NBS) (ECDRI, 2015). Pagano et al. (2019) assessed the effectiveness of NBS projects and demonstrated that NBS has positive effects on flood risk reduction and climate change adaptation. However, the lack of long-term observation records for any of these approaches has made it impossible to fully confirm the results.

China proposed the concept of the “sponge city” in 2012, which aims to adapt to environmental changes and increase a city's resilience to cope with natural disasters caused by rainfall-induced climate changes (Guan et al., 2021). While constructing a sponge city is a long-term process and it will require a high initial investment for construction, previous studies have demonstrated that a sponge city can effectively mitigate urban flooding (Hou et al., 2020; Li et al., 2020; Nguyen et al., 2019).

The International Conference on Flood Management (ICFM) evolved from the International Symposium on Flood Defence (ISFD), whose purpose was to discuss issues related to floods. Changing the name from “Defence” to “Management” reflected the shift of focus from flood defense and control to flood management, between 2000 and 2005; the theme of the first two conferences was flood defense, but by the third conference the theme had shifted from defense to management. From the fourth to the eighth conference the concept of flood management changed from vulnerability-based and risk-based to risk-based and resilience-based. At the ninth conference it changed further, from risk-based and resilience-based flood management to integrated resilience and sustainable flood management.

Previous review studies on flood management have mainly focused on flood risk assessment methods and flood inundation modeling, with less emphasis on detecting flood research trends (Aerts et al., 2018; Lyu et al., 2018; Teng et al., 2017). This report attempts to clarify the outline and timeline of flood research and focus on the following problems:

1) Research trends and keywords for flood research;
2) The relationship between traditional flood management and flood risk management;
3) Detailed flood risk assessment methods and flood adaptation strategies;
4) The relationship between flood resilience and flood risk management.

To explore these issues, we used the literature review method to survey the changing trends of flood management strategies according to development trends over time. Based on changing trends in flood management, we provide an overview of risk assessment methods and flood mitigation, adaptation, and resilience strategies, hoping to reduce the adverse consequences of flood events and help humans cope with compound flooding under the conditions of climate change and extreme weather events. Thus, we hope that the study results will provide more adaptation measures for coping with increasing floods, for future decision-makers. Section 2 describes the research thread: from flood control to flood resilience. Section 3 presents the definitions of risk and resilience, the framework, and a detailed approach to assessing flood risk and resilience. Section 4 discusses the differences between traditional flood management, risk-based flood management, and resilience-based flood management. Section 5 provides the conclusion of this study.

2. Bibliometric analysis

2.1. Keywords analysis

To obtain the current timely and critical issues in the area of flood disaster research, we used the keywords “flood,” “floods” and “flooding” for data collection, and we chose the publication years of January 2000 to December 2020. Ultimately, 29,931 publications were found in the Web of Science (WoS) core collection database. Next, we used the literature analysis tool VOSviewer and selected all keywords, author keywords, and “keywords plus” to reveal the hot-button issues and research trends of floods referred to in previous studies (Zhang et al., 2017). Author keywords were chosen by the author to best reflect the content of their research publications. “Keywords plus” means words that were generated by an automatic computer algorithm and extracted from the titles of the cited references by Thomson Reuters (Zhang et al., 2016). All keywords used were obtained by combining author keywords and keywords plus. Table 1 shows the top 20 most frequently used keywords and words with similar meanings that appeared in flood research during 2000–2020. Through these frequently-occurring keywords, we found that “urban” and “basin/river-basin/catchment” were the most frequent keywords, and thus that the current research scales for studying floods are mainly cities and watersheds. From the keywords “river,” “urban,” “flash” and “sea-level rise” we found that river floods, flash floods, urban floods and coastal floods are the types of flood disasters that are currently plaguing human beings. From the keywords “climate/climate change” and “precipitation/rainfall” we suspect that floods are becoming more frequent due to climate change and extreme rainfall. The keywords “model,” “GIS,” “hydrological modelling,” “machine learning,” “HEC-RAS” and “remote sensing” are the most popular methods in the field of flood research.

By perusing relevant literature and using the keywords “risk,” “risk assessment,” “risk management,” “vulnerability,” “hazard,” “management,” “adaptation,” “mitigation,” “uncertainty,” “damage/losses,” “resilience/recovery,” “forecasting” and “inundation,” we grouped current research content in flood research into the following six categories: flood risk analysis and assessment, hydrodynamic modeling and flood mapping, flood damage simulation, flood management, flood uncertainty analysis and flood forecasting. These categories are similar to those used in previous studies, which have used five categories: flood risk analysis and assessment, flood hazard mapping, flood damage assessment, flood management, and increasing the resilience of infrastructure (Mudashiru et al., 2021).

2.2. Evolution of the research terms

CiteSpace is used to detect frontier research topics through burst keywords, terms and references. In this study, we applied the network analysis tool CiteSpace to identify the terms with strongest citation bursts to assess the historic evolution and research trends of flood within the 29,931 articles we selected. The term “citation burst” represents the most active areas of relevant research terms and research hotspots that have gained considerable attention. This term refers to an easily visualized output from Citespace showing the most heavily used citations (strongest “citation bursts") and the citation bursts' start and end times. The “strength” represents the strength of a citation burst. Table 2 shows the top 25 terms with the strongest citation bursts. As can be seen from Table 2, the strongest citation burst is “flood forecasting” and the term's bursts started in 2000 and ended in 2013. The second strongest citation bursts were “flood frequency” and “climate variability,” which also had a duration of 13 years. The word pair with the highest strength is “flood frequency; ” its strength is 19.16 and the strongest citation burst occurred in the period of 2000–2012. Therefore, we can see that “flood forecasting” and “flood frequency” were the most popular and longest-lasting research topics. Detecting research terms on a time scale will reveal the trend of research topics over time.

This study through time is a change trend analysis of the research terms. Over the timeline of the literature review, the focus progressed from flood control to flood management to flood risk management to flood resilience. In the following content, this study will analyze the reasons for this evolution in research terms.

Table 1. Top 20 most frequently used title words, author keywords and keywords plus used during 2000–2020.

Rank	All keywords	Author keywords	Keywords plus
1	climate change	climate/climate change	climate/climate-change
2	Risk	Risk	model/models
3	resilience/recovery	Model	risk
4	hydrological modelling	Impact	precipitation/rainfall
5	GIS	precipitation/rainfall	impact
6	hazard	management	management
7	risk management	basin/river-basin/ catchment	basin/river-basin/ catchment
8	vulnerability	vulnerability	resilience/recovery
9	risk assessment	Water	vulnerability
10	remote sensing	River	frequency
11	urban	uncertainty	dynamics
12	frequency	simulation	river
13	rainfall/ precipitation	GIS	sea-level rise
14	adaptation	frequency	uncertainty
15	mapping	Runoff	prediction/forecasting/ perception
16	forecasting	inundation	flash
17	uncertainty	adaptation	simulation
18	mitigation	resilience/recovery	damage/losses
19	machine learning	variability	GIS
20	HEC-RAS	dynamics	runoff

Note: Keywords related to filters (e.g., “flood”) are not included in this table.

3. From flood control to flood resilience

3.1. Flood control

Flood control refers to changing the natural state of flooding through engineering measures, to reduce flood disaster. Flood control was first applied to control floods when humans realized that floods were inevitable but manageable. However, in the context of climate change, the risk of flooding is increasing, and the standards of flood control projects must change accordingly. Yet even after a series of flood control projects were implemented, flood disasters continued to occur, and human beings began to realize the limitations of flood control projects (Kundzewicz et al., 2019). For example, flood control projects age over time and therefore be continuously maintained and updated, requiring investments of manpower and financial resources (Rezende et al., 2019). Worse still, the cost of maintaining flood protection works may exceed the initial construction cost (Zevenbergen et al., 2020). In addition, the standards for flood control projects cannot be raised without considering factors such as cost effectiveness (Abdi-Dehkordi et al., 2021). Such realizations led to the introduction of the new term “flood management”: living with flooding, minimizing its losses and even deriving benefits from it where possible.

3.2. Flood management

Traditional flood management measures include structural and non-structural measures to reduce the adverse consequences of a flood event (Sayers et al., 2013)—detailed mitigation strategies as shown in Table 3. Traditional flood management measures tend to protect, reduce, or eliminate impacts and actions before an event (Peacock and Husein., 2012).

Implementing structural measures is more expensive than implementing non-structural ones. Structural measures require enormous ongoing costs for maintenance, and can lead to great losses if maintenance actions are incorrect or inadequate; furthermore, ecological impacts may be higher. Non-structural measures are less expensive and more sustainable than structural ones, while being more comprehensive and having fewer negative effects (Peacock and Husein., 2011). Previous studies have presented evidence that non-structural measures are easily implementable and more cost-effective than structural measures (Dawson et al., 2011).

In an effort to reduce the impact of flood disasters on human life and property, humanity has gone through thousands of years of water control experience. Societies have continuously improved flood control standards through engineering measures—to keep flood waters away from humans, and non-engineering measures—to keep humans away from flood waters. However, despite all efforts, the economic losses caused by flood disasters have not been reduced, and thus finding the optimal combination of engineering and non-engineering measures has become one of the hot topics in reducing flood disaster damage. However, from the perspective of disaster reduction, human intervention only minimally affects the occurrence of natural disasters. But humans can reduce the losses from natural disasters by reducing the assets exposed in flooded areas and decreasing the vulnerability of disaster victims, as well as strengthening disaster prevention and mitigation capabilities. Thus, flood management strategies based on both structural and non-structural measures have been transformed to risk-based flood management strategies.

3.3. Flood risk management

Flood risk management includes risk analysis, risk assessment and risk reduction. Risk analysis refers to the determination of the risks; risk assessment refers to the classification of the risks; and risk reduction refers to providing flood risk management strategies (Samuels et al., 2009). Flood risk assessment and management before a disaster can effectively reduce disaster losses (Dhiman et al., 2019; Lai et al., 2020; Pham et al., 2021). An accurate understanding of flood risk and its drivers is crucial for effective risk management (Muis et al., 2015). Therefore, it is essential to perform flood risk assessment and adopt appropriate flood management measures, engaging both ordinary citizens and flood managers, before a disaster occurs.

3.3.1. Flood risk

The concept of risk is not universally defined; different disciplines have different definitions of risk. But generally, risk is defined as (i) the uncertainty of future results; (ii) the uncertainty of the occurrence of losses; and (iii) the combination of the probability of future events and their possible consequences (Jonkman et al., 2003; Apel et al., 2008; Wang et al., 2019). For example, the IPCC AR3 report describes risk as a function of probability and consequence (IPCC, 2001); in IPCC AR5 risk is often represented as the probability of the occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur (IPCC, 2014), as shown in Table 4. In order to maximize the consistency of the use of IPCC groups, IPCC AR6 redefined risk as the potential adverse consequences for human or ecological systems, recognizing the diversity of values and objectives associated with such systems (IPCC, 2019).

In other words, there has been a transition from IPCC AR4 to IPCC AR5, from vulnerability-based to risk-based climate change adaptation concepts. Since this change, risk assessment research has received widespread attention. IPCC AR4 defined vulnerability as comprising three factors: exposure, sensitivity, and adaptive capacity (IPCC, 2007), the model as shown in Eq. (1). However, in IPCC AR5, vulnerability includes two elements: sensitivity, and capacity to cope and adapt (IPCC, 2012), the model as shown in Eq. (2).

The IPCC SREX report defined the risk determined by climate and weather events (the hazards), exposure, and vulnerability (IPCC, 2012). IPCC AR5 defined the risk framework interactions among vulnerability, exposure, and hazard (IPCC, 2014), the model as shown in Eq. (3). The flood risk defined in recent studies has been based on the risk framework defined in IPCC AR5; it is determined by vulnerability, exposure, and

Table 2. Top 25 terms with the strongest citation bursts.

Terms	Strength	Begin	End
flood frequency	19.16	**2000**	2012
flood forecasting	16.33	**2000**	2013
sensitivity	3.65	**2000**	2005
flood control	6.83	**2002**	2008
climate variability	5.81	**2002**	2015
flood management	6.33	**2003**	2009
flood hazard	5.33	**2004**	2007
flood warning	4.05	**2005**	2011
uncertainty	5.31	**2007**	2009
climate change	4.66	**2007**	2016
flood risk	4.12	**2008**	2011
sensitivity analysis	3.38	**2011**	2015
flood losses	3.72	**2013**	2017
flood insurance	3.29	**2015**	2017
flood mitigation	7.01	**2018**	2021
flood susceptibility	5.45	**2018**	2021
hazard assessment	4.75	**2018**	2021
flood mapping	3.57	**2018**	2021
flood risk management	3.43	**2018**	2019
climate change adaptation	3.37	**2018**	2021
water management	3.29	**2018**	2019
health	5.04	**2019**	2021
flood resilience	3.97	**2019**	2021
flood vulnerability	3.73	**2019**	2021
mitigation measure	3.49	**2019**	2021

Table 3. Flood management measures.

Measures	Description
Structural	Keeping water away from populations, for flood hazard reduction. Measures include dams, dikes, levees, weirs, seawalls, dykes, reservoirs, pump stations, embankments, tidal gates, diversion channels, etc.
Non-structural	Keeping populations away from water bodies, for flood vulnerability reduction. Measures include policies and laws, raising public awareness, flood forecasting and warnings, evacuation, training and education, land use adjustment, regulations and insurance, funding and subsidies, spatial and flood management plans, etc.

hazard. Vulnerability includes the concepts of sensitivity and adaptive capacity, the model as shown in Eq. (4).

$$Vulnerability = f(Exposure, Sensitivity, Adaptive\ Capacity) \tag{1}$$

$$Vulnerability = f(Exposure, Adaptive\ Capacity) \tag{2}$$

$$Risk = f(Hazrad, Exposure, Vulnerability) \tag{3}$$

$$Risk = f(Hazrad, Exposure, Sensitivity, Adaptive\ Capacity) \tag{4}$$

3.3.2. Flood risk assessment

The risk assessment of natural disasters includes qualitative, semi-quantitative, and quantitative approaches. The result of qualitative assessment is the relative magnitude of natural disaster risk, such as zero risk, low risk, medium risk, and higher risk (Ming et al., 2022). The result of semi-quantitative risk evaluation can be expressed as the multiplication of the frequency grade and consequence grade (Bai et al., 2013). Quantitative assessment converts the loss result into a monetary value, to obtain an expected loss, such as the expected annual loss (EDA) or the cumulative loss. In order to accurately measure the impact of flood

Table 4. Risk as defined in the IPCC reports.

Definitions of risk	Reference
Risk is a function of probability and consequence Risk = Probability × Consequences	(IPCC, 2001)
Risk is often represented as the probability of the occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur.Risk = (Probability of Events or Trends) × Consequences	(IPCC, 2014)
The potential for adverse consequences for human or ecological systems, recognizing the diversity of values and objectives associated with such systems	(IPCC, 2019)

disasters on human societies and economies, flood risk assessment has undergone a change from qualitative to quantitative. According to different research needs, flood risk assessment could choose the research scale (i.e., global, country, basis, city, community) (de Moel et al., 2015). When conducting flood risk assessment, it can be assessed according to different years to observe the characteristics of changes in flood risk over time. In addition, it can be assessed according to specific scenarios, such as different flood return period scenarios, different social development scenarios, and different flood adaptation scenarios (Cheng et al., 2013; Penning-Rowsell et al., 2013; Shan et al., 2019).

The most frequently used expressions of risk assessment models are the expressions of "addition" and "multiplication". The expression based on "plus" is a linear risk evaluation model; the equation for calculating the flood risk is defined in Eq. (5). The expression based on "multiplication" is an index model; the equation for calculating the flood risk is defined in Eq. (6).

$$Risk = w_1 \times Hazard + w_2 \times Exposure + w_3 \times Sensitivity + w_4 \times Adaptive\ Capacity \tag{5}$$

$$Risk = Hazard^w \times Exposure^w \times Vulnerability^w \tag{6}$$

Flood risk assessment from hazard, exposure, and vulnerability deals with the relationship between floods and humans. This approach can identify more effective counter-measures from these three components, for disaster risk reduction. Koks et al. (2015) deem flood risk assessment to be estimates of the loss of life and economic damage. Traditional methods include a probability evaluation method based on historical data, comprehensive flood risk assessment, flood risk assessment integrating remote sensing and a geographic information system (GIS), and the Source-Pathway Receptor conceptual model. Nowadays, in the era of big data and the synthesis of flood risk assessment approaches, the risk assessment approach is being increasingly oriented toward scenario-based methods (Zhang et al., 2020). The following section describes flood risk assessment in detail. A synthesis of flood risk assessment approaches includes the three indicators of hazard, exposure, and vulnerability. A scenario-based flood risk assessment requires (1) a hydrodynamic model and (2) flood damage simulation.

3.3.2.1. Synthesis of flood risk assessment approaches. Most risk assessments belong to the category of comprehensive assessment. Comprehensive assessment means to make a general assessment of the index data extracted from different aspects of objective entities. The first step is to build an evaluation index system, such as selecting an index system from the three indicators: hazard, exposure, and vulnerability. Some studies have taken the perspective of systems theory, such as disaster-pregnant environment, disaster-causing factors, disaster-bearing bodies and defense capabilities; the indicator system is selected in terms of these aspects. The second step is to select each index factor and collect its related data (Asbridge et al., 2021; Roy et al., 2021); Figure 1 shown the detailed indicators of the three elements of risk. When selecting indicators, the indicator systems should be considered according to the principles of purposeful, systematic, scientific and actionable. When selecting data, the actual situation of the study area and the difficulty of data acquisition should be considered. Third, the weight of each index and factor is determined by certain mathematical methods, such as AHP, the entropy weight method, the fuzzy comprehensive evaluation method, etc. Finally, hazard, exposure, vulnerability and adaptability are calculated by either a linear or an exponential evaluation model, to obtain the results of flood disaster risk analysis (Jiang et al., 2008).

3.3.2.2. The simulation-based flood risk assessment approach. Analyzing the risks of flood disasters in advance is an effective approach to alleviating the losses induced by floods. The simulation-based approach merges multidisciplinary approaches, which can not only calculate flood risk but also simulate the flood evolution and evaluate damage losses. Therefore, more and more studies are applying this method to carry out flood risk and flood losses research (Li et al., 2016).

According to the framework of risk assessment, simulation-based flood risk assessment can be divided into two parts. The first part is a hydrological and hydrodynamic model based on a hazard analysis to obtain a flood inundation map. The second part is a damage estimation model based on vulnerability and exposure analysis to obtain disaster loss results. The simulation process is shown in Figure 2.

(1) Hydrological and hydraulic models based on hazard analysis

A hydrological model is used to simulate the runoff and confluence process of a watershed. It can simulate the runoff process of rainfall from the source, to obtain the flow processes and flow peak values of different sections of the rivers, but it cannot determine the hydraulic elements of the river or the flood inundation range of the watershed. The hydrodynamic model can simulate the evolution of floods and can directly reflect the inundation range and depth of floods in the form of a watershed inundation map, but it cannot simulate the hydrological process from sources such as precipitation, evaporation, or runoff. After coupling the hydrological model with the hydrodynamic model, the flow process of the channel section simulated by the hydrological model can be used as the input to the upstream boundary conditions of the hydrodynamic model, which reflects the runoff change in the basin and the evolutionary process of the flow in the river.

(2) Damage estimation model based on vulnerability and exposure analysis

The damage estimation model is usually adopted to estimate the damage costs of flood disasters. Questionnaire survey and stage-damage functions are two basic methods for conducting flood damage estimations (Win et al., 2018). A questionnaire survey is a reliable method, but is expensive in terms of both funding and time. The stage-damage function method is therefore more widely used than the questionnaire survey, for estimating flood damage.

The stage-damage functions method comprises the following four procedures:

a) Identify exposed elements and collect relevant socioeconomic data;
b) Calculate the exposed asset value in each unit;
c) Build the stage-damage curve according to flood water's inundation depth and the receptor loss rate;
d) Calculate direct monetary damage according the stage-damage curve and asset value in each unit.

A stage-damage curve describes the change of the damage fraction of different receptor types, with the change in the flood inundation depth. However, the relation between inundation depth and damage fraction is uncertain, as it can vary among different regions. It is difficult to measure if the stage-damage curve is used in multiple regions, as this will add extra uncertainty to the modeling process (Scorzini and Frank, 2017). On the other hand, the scenario-based flood risk assessment approach can simulate the dynamic process of flood occurrence and quantitative disaster loss results, but because of its high requirements for basic data, it poses great operational difficulty.

3.3.3. Flood risk management strategies

Flood risk management means minimizing the loss of life and economic damage by flood disasters or reducing the probability, and the adverse consequences, of flooding. Flood risk management includes not only implementing structural measures to reduce the possibility of flooding (reducing hazard) but also using non-structural measures to reduce the amount of assets exposed and the vulnerability of receptors. Sayers et al. (2013) reported that the purpose of flood risk management strategies was to achieve four goals: (i) reduce risk to people and

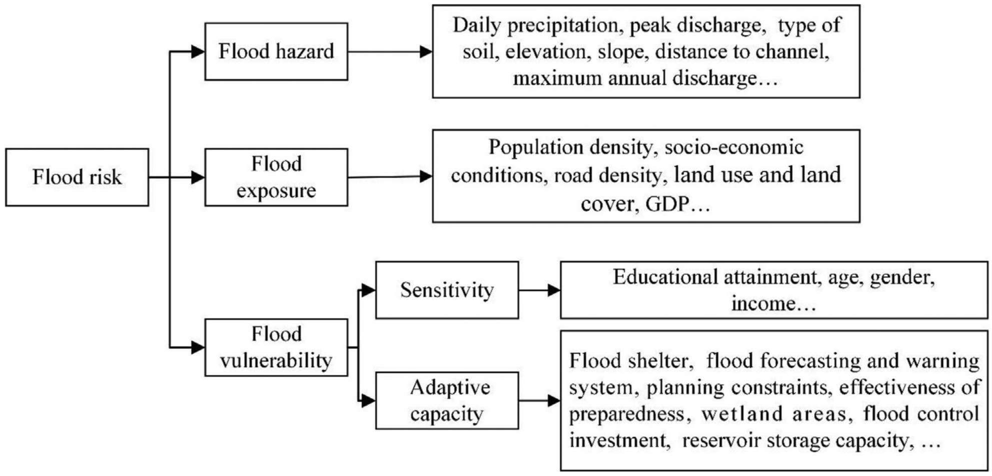


Figure 1. Summary of the indicators of the three elements of risk.

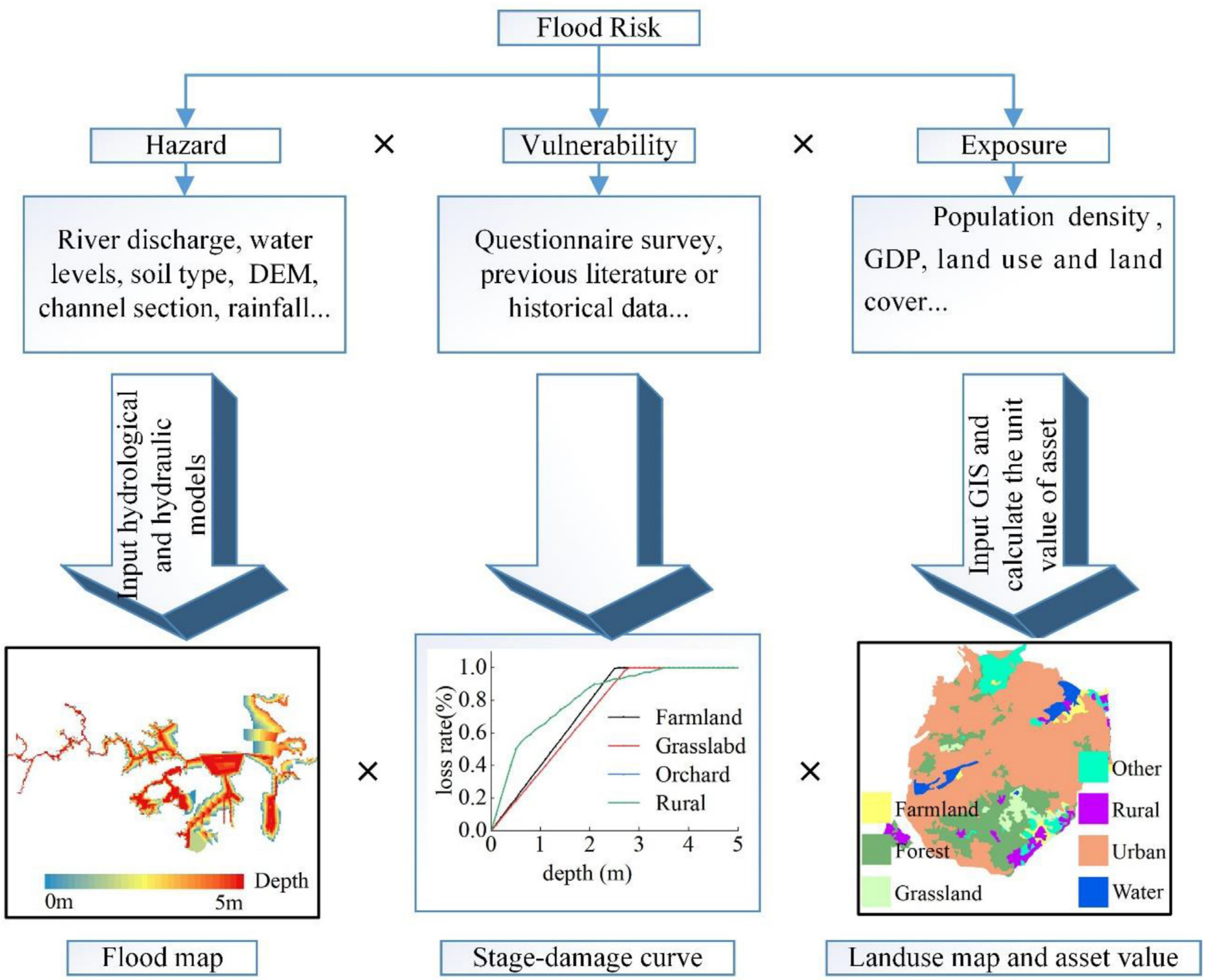


Figure 2. Framework of simulation-based flood risk assessment approach.

communities, (ii) reduce risk to and promote economies, (iii) promote ecosystem goods and services, and (iv) promote social well-being.

Some literature have used the three elements of flood risk to provide flood risk management (FRM) strategies, such as reducing the exposure of humans, the economy, and the ecosystem to flooded areas and reducing the vulnerability of those exposed to floods (Koks et al., 2015; Sayers et al., 2013). Other literatures have used a flood risk management (FRM) framework to provide flood risk management strategies (FRMSs), which include flood defense, flood prevention, flood mitigation, flood preparation and flood recovery

(Dieperink et al., 2016; Hegger et al., 2014; Raadgever and Hegger, 2018). At the same time some studies have put forward flood risk management strategies based on the Source-Pathway Receptor conceptual model.

3.4. Flood resilience management

3.4.1. Flood resilience

Flood risk is increasing with climate change and socio-economic development. Therefore, current flood risk management measurements are not sufficient to cope with today's flood risk (Rezende et al., 2019; Ward et al., 2017). The concept of resilience has been widely used in recent academic literature and policy documents. IPCC AR6 defines resilience as the ability to bounce back after a disturbance and returning to the previous state, and adaptation is often organized around resilience (IPCC, 2022). Table 5 shows the definitions of resilience in IPCC, UNISDR and other reports.

3.4.2. Flood resilience assessment

Flood resilience focuses on building flood resilience indicators and evaluating flood resilience, in the primary literature. The major flood resilience evaluation are based on the semi-qualitative approach, to select the indicator systems or interviews from various dimensions and express the importance of flood resilience. Table 6 presents the dimensions of resilience in previous studies, and the research scale. Sun et al. (2016), based on the methods of analytic network process evaluation flood disaster resilience in the Chaohu Lake Basin, developed an index system for evaluating regional flood disaster resilience, and a flood resilience index system that included five dimensions (nature, society, economy, technology, and management). Luo et al. (2021) evaluated flood disaster resilience in the Yangtze River Basin based on the hesitant fuzzy linguistic term and pointed out that the flood resilience index system includes five dimensions—nature, society, economy, infrastructure, and management. Other researchers have evaluated flood resilience based on resilience theory (robustness, rapidity, redundancy, and resourcefulness) (Lee et al., 2021). Resilience can also be measured by the time a receptor needs, to recover from shock (Park et al., 2021).

3.4.3. Flood resilience management strategies

Many projects have been put forward, that focus on building resilient communities, resilient cities, and resilient coastal areas. The Resilient Communities Project, the 100 Resilient Cities program, and the Sustainable and Resilient Coastal Cities program are examples that have been implemented in various countries. Some institutions and international teams, such as the OECD, are also building resilient cities; the Rockefeller Foundation pioneered a project to build 100 resilient cities; and a smart, sustainable and resilient cities project has been implemented by the G20.

Most flood resilience management strategies use a resilience framework to provide management strategies (Abdi-Dehkordi et al., 2021; Kim et al., 2017; Rezende et al., 2019). The community resilience framework is based on four main components (economic activities, ecosystem services, infrastructure and buildings, and community action) and their sub-categories, to provide detailed resiliency solutions (https://resilientvirginia.org/). The framework also defines the characteristics of resilience (aware, diverse, self-regulating, integrated, and adaptive) as detailed indicators, and provides resilience strategies for each indicator (Rodin, 2013). The resiliency solutions could quickly bring infrastructure such as buildings back to its initial (pre-disaster) state, and the community/city could also recover quickly, perhaps even attaining a state better than its pre-disaster one (Cariolet et al., 2019; Koren et al., 2017).

We need to explain the difference between infrastructure resilience and community/city resilience. A disruptive event can be divided into three stages: before disruption, during disruption, and after disruption. When disruptive events occur, infrastructure has four resilience properties, defined as the 4R's: Robustness, Redundancy, Resourcefulness, and Rapidity, and a community/city has five resilience properties: Robustness, Redundancy, Rapidity, Resourcefulness, and Adaptivity. The similarity between these two types of resilience characteristics—engineering and community/city—is that the system can experience a disturbance and still retain control of its function and structure.

Some infrastructure, such as buildings and roads, etc., is in the domain of engineering resilience. When disruptive events occur, engineering resilience will enable the infrastructure to recover to its initial state within a defined timeline, as shown in Table 7. Communities and cities, by contrast, belong to the category of socio-ecological resilience; after a disturbance, they will reach a new equilibrium within a defined timeline. Because the operation of a city involves human interaction with natural systems, such a system can learn from past disasters and improve its ability to adapt to disasters, establishing a new equilibrium that will be better than the initial state of the resilient city system.

Table 5. Resilience defined in IPCC and UNISDR reports.

Reference	Definition of resilience
UNISDR, 2017	The ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management.
National Research Council, 2010	Resilience generally refers to "a capability to anticipate, prepare for, respond to, and recover from significant multi-hazard threats with minimum damage to social well-being, the economy, and the environment."
IPCC, 2014	The capacity of social, economic, and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation.
IPCC, 2022	The capacity of social, economic and ecosystems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure as well as biodiversity in case of ecosystems while also maintaining the capacity for adaptation, learning and transformation.

Table 6. The dimensions of resilience in previous studies.

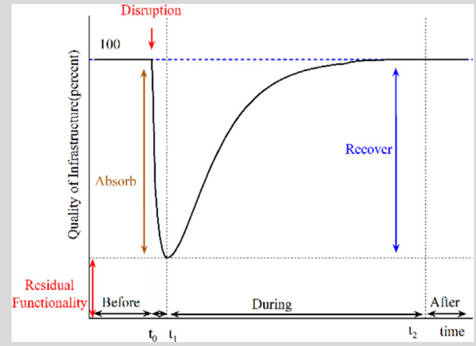
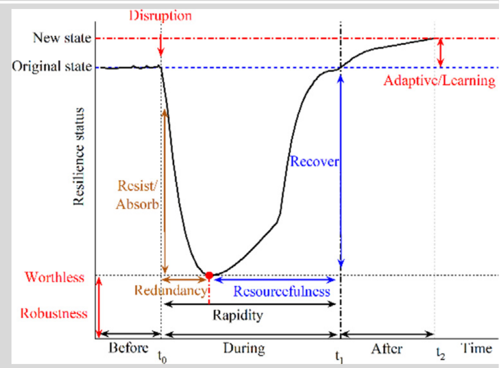
Authors & Year	Definition	Research scale
Sun et al. (2016)	nature, society, economy, technology and management	River Basin
Luo et al. (2021)	nature, society, economy, infrastructure and management	Lake Basin
Chen et al. (2013)	physical, social, and economic	City
Laurien et al. (2020)	human, financial, natural, physical, and social	Community
Moghadas et al. (2019)	social, economic, institutional, infrastructural, community capital and environmental	Urban

4. Discussion

4.1. Trends in historical research

We applied the software of CiteSpace to identify the research trends and timelines from 29,931 articles. Figure 3 summarizes the timelines, measures, and research purposes from flood control research to flood management research from 2000 to 2020. The research about flood management strategies was divided into four distinct phases of its development, which are shown in Figure 3.

Table 7. Resilience properties and the schematic of resilient system.

System attribute	Resilience properties	Schematic (Performance of resilient system)
Engineering resilience (building, road, etc.)	Robustness, Redundancy, Rapidity, and Resourcefulness	
Socio-ecological resilience (community, city)	Robustness, Redundancy, Rapidity, and Resourcefulness, Adaptive	

a). Phase-I: From 2000 to 2003, the concept of flood management is using structural measures to control floods. Protecting Life and Property from flooding was the advantage of defense measures; however, it is expensive to install and maintain, and it will reduce the biodiversity around embankments and dams (Liao et al., 2019; Sharafati et al., 2020).

b). Phase-II: From 2003 to 2008, the concept of traditional flood management aimed to reduce the impact of flood events; however, it failed to deal with over-standard floods and difficulty addressing the uncertainty of flood events (Anita, 2013). Flood mitigation measures aim to reduce the losses from flood disaster while including structural and nonstructural measures to cope with flooding.

c). Phase III: From 2008 to 2017, flood risk management is cost-effective and has environmental benefits, while there are always residual risks, and it is difficult to eliminate residual risk (Bischiniotis et al., 2020; Merz et al., 2010). Flood adaptation measures are aimed at reducing vulnerability, effects and undertaking actions to strengthen and adjust the existing mitigation measures against the adverse effects of floods; these measures include soft adaptation and hard adaptation (Du et al., 2020; Logan et al., 2018).

d). Phase IV: 2017 to 2020 onwards. Flood resilience measures aim to reduce and transform the risk of flood damage and quickly recover the system to its pre-flood state after flooding; it focuses on absorptive coping capacity, adaptive capacity, transformation capacity and anticipatory capacity (Mahzarnia et al., 2020; Saja et al., 2019).

We can see that flood management measures are continually being optimized, and research purposes are becoming more diverse. After the concept of sustainable development and the promotion of some international conferences, people gradually realized the limitations and disadvantages of the previous management measures, so the flood management measures have gradually changed to more sustainable strategies. Flood defenses measure fail to deal with over-standard floods. Traditional flood measures cannot address changing flood risks. There is always residual risk in flood risk management. Therefore, the resilience measure gradually becomes a new trend in flood management.

4.2. Flood risk management and flood resilience

Recently, there has been more research on flood resilience than on flood risk management. Previous studies put forward three relationships between resilience and risk management: resilience as the goal of risk management, resilience as part of risk management, and resilience as an alternative to risk management (Suter, 2011). Nevertheless, this study has taken the approach of resilience as part of risk management, because resilience as an alternative to risk management is too radical to consider seriously at this time. However, risk is inherently unpredictable, and it is impossible to prevent risks completely. Thus, some residual risk always exists.

Flood risk management requires human recognition; however, human recognition can never be complete or absolute. Therefore, flood risk management has the limitation of not being able to eliminate all risks. If resilience could deal with the remaining risks and complement the inherently insufficient risk management, it would be beneficial to increase resilience. Further research, therefore, will focus on how to build resilience and evaluate resilience to complement the inherently insufficient risk management. Comparing risk-based flood management strategies with resilience-based flood management strategies, as shown in Figure 4, we find the advantage is that the resilience-based flood management strategies enables the receptor to recover during an event. Thus resilience-based flood management strategies may enable a system to recover to a state that is better than its pre-disaster state, because of the capabilities of self-organization, learning, and adaptation. Because flood resilience can cope with unexpected climatic perturbations and is self-organizing (McClymont et al., 2019), flood risk management has shifted toward more resilience, such as NBS, blue-green infrastructure, LID, GI, or SCP.

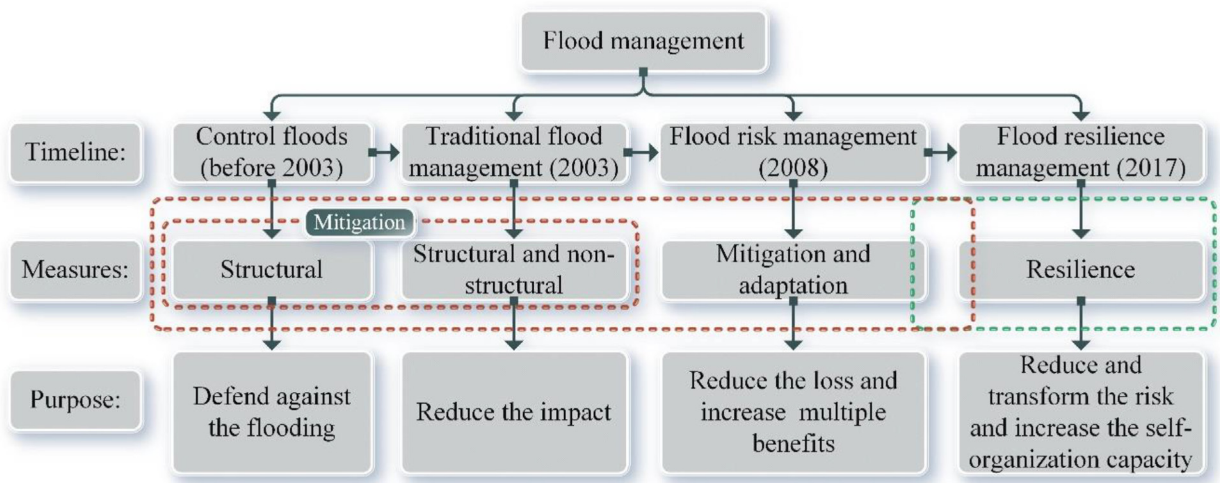


Figure 3. Research trends of flood risk management.

4.3. Future research trends

IPCC AR5 shows that extreme precipitation events will become more intense and frequent in many parts of the world (IPCC, 2014). A combination of climate change mitigation and adaptation measures applied simultaneously is most conducive to mitigating the negative impacts of climate change on humans (Yamamoto et al., 2021). Previous researches have shown that adapting to climate change is a good way to address a range of problems caused by rising temperatures and sea levels (Xu et al., 2019). Mitigation measures aim to reduce global greenhouse gas emissions to mitigate the effects of global warming. Zhou et al. (2018) found, however, that climate change adaptation was more effective in reducing future flood volumes than was climate change mitigation. For example, representative concentration pathways (RCPs) and shared socioeconomic pathways (SSPs) aim to stabilize the concentration of greenhouse gases in the atmosphere. However, mitigation measures have limitations. Even if appropriate mitigation measures are developed and implemented, temperature increases will continue for centuries (IPCC, 2007; IPCC, 2014).

With the release of IPCC AR6, the concept of climate change resilience will become the hot-spot and research frontier in the future. Climate resilience is a new direction for coping with climate change, although climate change mitigation and adaptation will continue to be important. Human and natural systems can build resilience through adaptation, mitigation, and sustainable development (IPCC, 2021). Because resilience has the advantages of transformation, self-organization, and learning capacity, flood management will trend toward resilient management strategies in the future. Therefore, implementing flood resilience strategies, evaluating flood resilience, detecting new problems in resilience theory, and improving resilience through intervention measures will be hot issues in future flood research; indeed, they are already becoming more popular research approaches.

Flood risk is a dynamic process that changes with drivers, such as climate change, urbanization, sea-level rise, land subsidence, and socioeconomic development. Therefore, how to improve the Spatio-temporal resolution of flood risk assessment to provide more detailed flood risk information for disaster risk reduction will become a future research direction. Compound disasters and multi-hazard events will further aggravate the impact of disaster events, such as Australia's drought-wildfire-heavy Rain Event in 2019/2020 and Floods events under the COVID-19 pandemic (Kemter et al., 2021; Simonovic et al., 2021). In addition, with the development of the Internet, the occurrence-development-impact of a flood disaster event will be quickly discussed by the public, so the management of disaster events will bring huge challenges to managers.

Therefore, how to play the function of resilience in robustness and redundancy to ensure the normal operation of infrastructure during the process of extreme disasters will become one of the important tasks in the future. Secondly, resilience management should fully exert the people's subjective initiative and adjust adaptive means according to the current flood risk at any time. To maximize benefits, how to fully integrate the four dimensions of resilience management (i.e., Plan, Absorb, Recover, Adapt) and risk management (i.e., Mitigate, Prepare, Respond, Recover) will become a future research focus. In addition, the R&D and application of new technologies will also become an important tool for disaster

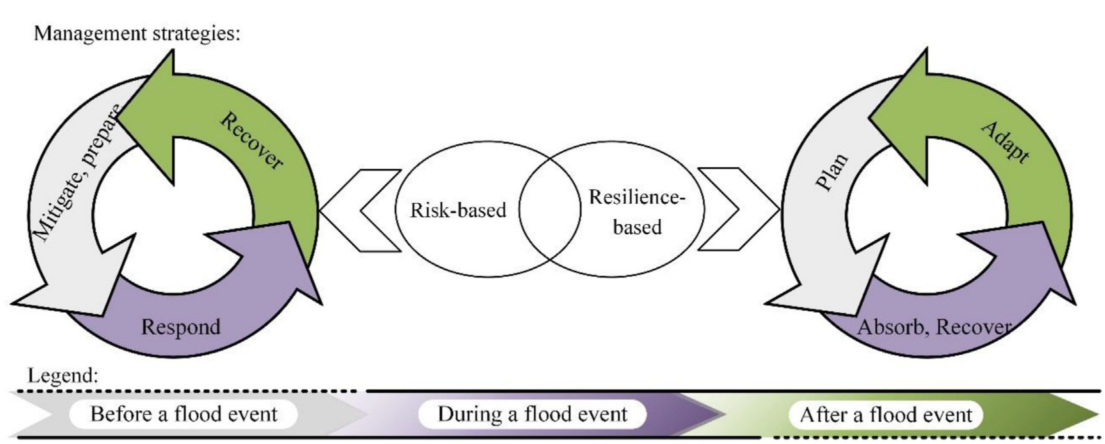


Figure 4. Risk-based and resilience-based flood management strategies.

resistance and rescue in the future, thus continuously replacing the traditional management methods in the past. For example, combined mobile flood walls are used to protect the urban areas and resist floods. The drones provide precise positioning services for disaster relief; the waterlogging truck is used to quickly drain the waterlogged water. The emergency-powered boat bridge is used to transfer the trapped people.

5. Conclusion

This study used bibliometric tools and selected 29,931 academic literature to explore the changing trends of research topics in the flood management field over time. We have also presented detailed content on the definition of risk, risk analysis methods, flood management, flood risk management, flood resilience, and corresponding implementation strategies. Flood management is transitioning from risk-based to resilience-based. Hence, we explored the links between flood defense, flood management measures, flood risk management strategies, and flood resilience management strategies. This study shows that flood control strategies have been unable to respond to today's flood environment. Flood risk is unavoidable but manageable; it can be minimized or diverted through engineering and non-engineering measures. Flood risk management embeds the concept of a continuous adaptation process, replacing the approach of implementing and maintaining flood control measures. Flood resilience embeds the concept of sustainability, integrated with the concept of a continuous process of adaptation, in flood risk management. Flood management strategies will be re-integrated with sustainability, resilience and adaptation, in the future.

By comparing flood mitigation, adaptation, and resilience measures, we find that mitigation measures aim to resist flooding and take action, and adaptation measures have accepted the inevitability of flood events and adjusted the mitigation measures, thus becoming more suited to the actual environment. Because resilience measures focus on learning from the experiences of flood events, this approach can lead to better adaptation measures. Flood risk management integrates flood mitigation and adaptation to cope with flood events, and flood resilience can therefore reduce and transform damage risk. This study prefers the view of integrating the concept of resilience into the framework of risk management. However, although flood resilience management strategies have advantages over flood risk management strategies, it is unreasonable to attempt to replace risk management completely.

This report provides new insight into flood research trends, by examining current research frontiers, and clearly shows a timeline for flood research. It will help stakeholders understand the advantages of the different strategies of traditional flood management, flood risk management, and flood resilience. The next step for stakeholders is facing uncertain climates, diverting human-induced disasters, and building more resilient communities, cities, and watersheds. This study suggests flood adaptation and mitigation measures along with the integration of the dual strategies of flood risk management and flood resilience, to effectively reduce water-related adversities.

Declaration

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

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Data availability statement

No data was used for the research described in the article.

Declaration of interest's statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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