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## a review and reflection

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ORIGINAL PAPER

# Risk assessment methods of cascade reservoir dams: a review and reflection

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## Abstract
Risk assessment of cascade reservoir dams is not only the key to ensure the safety of the basin, but also the objective requirement of dam risk management. Based on the development status of cascade reservoirs in China, the complexity of dam risk management of cascade reservoirs compared with a single reservoir was analyzed. By reviewing the advances on the studies of dam risk in cascade reservoirs, this paper summarized their limitations in terms of scientificity and practicability. Moreover, some concepts and methods were proposed on the risk assessment of cascade reservoirs: (1) The dam risk of a cascade reservoir was decomposed into own risk and additional risk, the consequence of its dam breach was decomposed into direct loss and potential loss, and an influence coefficient was defined to reflect the risk transmission and superposition degree among cascade reservoirs; (2) The related concepts and formulas for the calculation of dam risk probability and consequence of cascade reservoirs were proposed, which realized the transition of dam risk assessment method from a single reservoir to cascade reservoirs; (3) A project rank classification method for cascade reservoirs was proposed, which took into account not only the project scale and benefits in socioeconomic development, but also the successive dam breaches possibility and consequences. This study is of great significance to clarify the focus of future research and promote the practical application of dam risk management in cascade reservoirs.

**Keywords** Cascade reservoirs · Dam breach · Risk transmission · Risk assessment · Probability

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## 1 Introduction

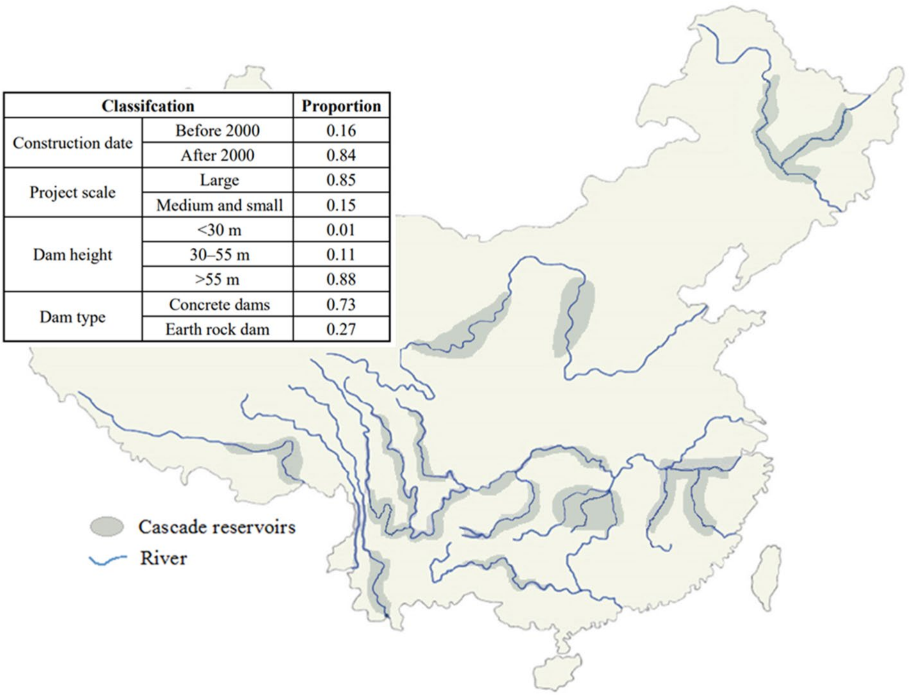
In order to make full use of the hydropower resources, the cascade development model has been chosen on more and more rivers in the world, such as the Tennessee River in the USA, the Rhone River in France, the Columbia River flowing through Canada and the USA (Guertault et al. 2018; Makaske et al. 2017; Miranda et al. 2017). At present, hydropower construction in China is at the peak concerning the development of cascade reservoirs in river basins. A series of cascade reservoirs have been planned and constructed, such as the Maotiao River cascades, Hongshui River cascades and Wujiang River cascades that have been basically completed, and the Dadu River cascades, Yalong River cascades and Nujiang River cascades under construction (Fan et al. 2015; Yang et al. 2016; Zhou et al. 2018). Despite generating enormous economic benefits, dams may break and cause destructive floods, resulting in giant threats to the downstream residents and the socio-economic (Fan et al. 2015; Latrubesse et al. 2017; Zhang et al. 2021a). Compared with ordinary reservoirs, the dam risk in cascade reservoirs has transmission and superposition effect. One of the cascade dams breaks can easily lead to successive dam breaches in downstream reservoirs, resulting in serious losses. In May 2020, heavy rainfall in Michigan led to the breaches of two cascade dams, the Edenville Dam and Sanford Dam, resulting in the emergency evacuation of more than 10,000 residents and the destruction of infrastructure downstream (Mehta et al. 2020). In July 2021, the "Yongan-Xinfa" cascade reservoirs in the Nenjiang River Basin in China collapsed, causing 16,660 residents to be affected and 217 $Km^2$ of farmland to be flooded (Wang et al. 2022).

With the transformation from safety management mode to risk management mode in China, risk analysis and assessment has been widely recognized by researchers, regulators and professionals as an important way for reservoir dams management (Ge et al. 2020a, b). Accordingly, the relevant theories and methods for a single reservoir dam is becoming more and more abundant (Huang et al. 2017; Li et al. 2018, 2019). However, there is a lack of clarity and consensus in the way dam risk in cascade reservoir has been conceptualized and quantified, because of the uncertain risk factors, the complex risk mechanism, and the serious consequence of dam breach (Cai et al. 2019; Zhou et al. 2018).

In order to clarify the focus of follow-up research and improve the scientificity and practicability, the authors carried out a structured review of the dam risk study of cascade reservoirs and explored the key issues with a theoretical discussion of risk analysis and assessment for cascade reservoirs. According to the source of risk and the impact scope of dam breach, the risk and consequence of dam breach in cascade reservoirs were decomposed, respectively. Subsequently, the risk transmission and superposition effect was quantified, the relevant concepts and formulas for the calculation of risk probability and consequence were proposed. Moreover, several key issues and suggestions were presented to provide useful information for scholars in their future research.

## 2 The development status and risk management of cascade reservoirs in China

At present, cascade reservoirs account for 48% of China's built reservoir projects and 50% of the reservoir projects under construction (Fan et al. 2015). By 2050, 13 hydropower bases will be built in Jinsha River, Yalong River, Dadu River, Wujiang River, Yangtze




| Classifcation | | Proportion |
|---|---|---|
| Construction date | Before 2000 | 0.16 |
| | After 2000 | 0.84 |
| Project scale | Large | 0.85 |
| | Medium and small | 0.15 |
| Dam height | <30 m | 0.01 |
| | 30–55 m | 0.11 |
| | >55 m | 0.88 |
| Dam type | Concrete dams | 0.73 |
| | Earth rock dam | 0.27 |

**Fig. 1** Distribution of cascade reservoirs in China

River and Lancang River, et al. including 310 large and medium-sized cascade reservoirs (Liu et al. 2021; Wang et al. 2020; Zhou et al. 2020). Cascade reservoirs construction meets the river hydrological characteristics and the requirements of socioeconomic development, which has become a basic form of water energy resources utilization in major river basins of China (Zhou et al. 2018, 2020). Wang et al. (2020) made statistics on the distribution of cascade reservoirs in China, as shown in Fig. 1.

Geographically, cascade reservoir groups in China are mainly concentrated in the west, especially in the southwestern region. They mostly located on the first and second terraces of China's land terrain, with a large water-level difference, which is conducive to the full utilization of hydro energy resources (Fan et al. 2015; Liang et al. 2017). In terms of dam type, concrete dams are more common in cascade reservoirs, mainly because they have a low probability of dam breach than earth rock dams (Fan et al. 2015; Hariri-Ardebili, 2018; Kalinina et al. 2018; Rezaiee-Pajand et al. 2021). In addition, with the rapid development of hydropower construction and the continuous improvement of engineering technology, the scales of the cascade reservoir groups are also increasing. For example, 13 cascade hydropower stations are planned to be built in Jinsha River, with a total reservoir capacity of 99.1 billion $m^3$ and an installed capacity of 83,000 MW; 22 cascade hydropower stations are planned to be built in the main stream of Dadu River, with a total storage capacity of more than 16.5 billion $m^3$ and an installed capacity of 25,000 MW, as shown in Fig. 2. (Fan et al. 2015; Liu et al. 2021).

From the perspective of risk management, the cascade reservoir dams in China currently adopt the design standards and methods of a single reservoir (Zhou et al. 2018).

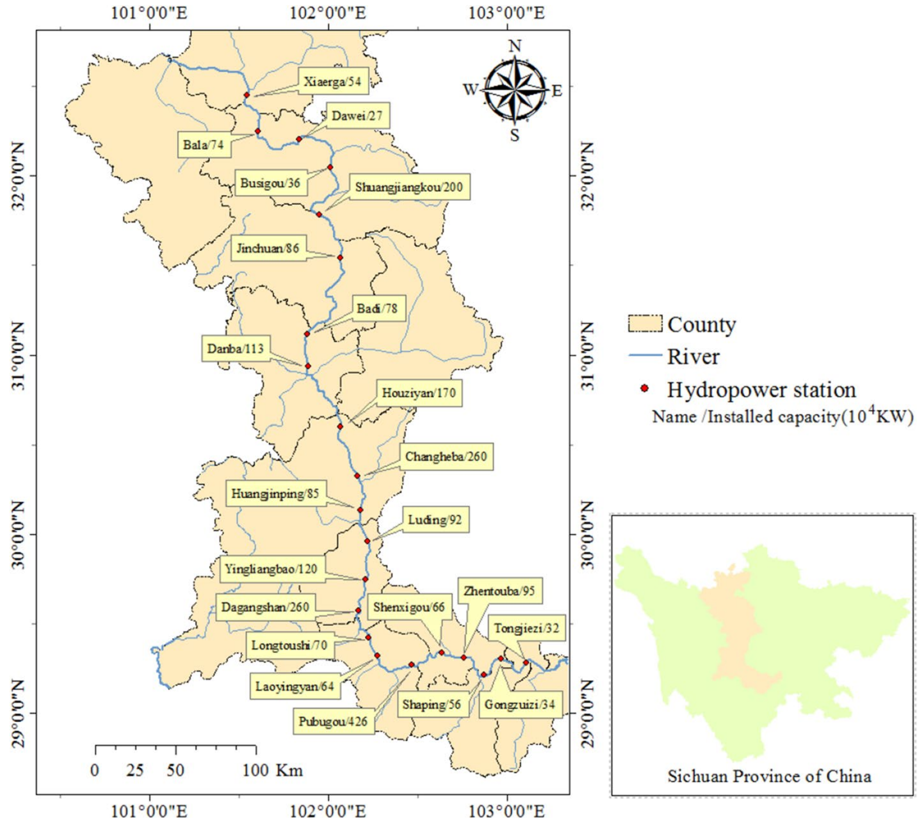



**Fig. 2** Layout of the cascade reservoirs planned in Dadu River Basin

Although the complexity of a cascade reservoir group compared with a single reservoir is considered in the construction and management, more attention is paid to how to maximize its comprehensive benefits (Lu et al. 2018; Shang et al. 2018), and the risk sharing of a cascade reservoir group is not considered from the perspective of the whole basin. At the level of natural factors, over-standard floods, earthquakes, and weirs formed by landslides are the main risk sources for the cascade reservoir dams (Chen et al. 2017; Li et al. 2019; Yang et al. 2016; Zhou et al. 2020). The local failure of a dam often affects the whole body, and a dam breach can easily form a "domino effect," leading to the successive breaches in downstream cascades (Zhang et al. 2018). At the level of management system, due to the many participating units and cross-operation, it makes a lack of linkage and articulation of emergency plans among the various cascade power stations in the same basin (Hennig et al. 2013; Shang et al. 2018; Zhou et al. 2018). Correspondingly, a coordinated and unified basin safety management and risk prevention system has not yet been formed. At the level of social factors (Ge et al. 2021; Hu et al. 2020; Zhou et al. 2015a, b, c, d), once the unified scheduling and coordination of the cascade reservoirs are not properly supervised, it will cause not only the waste of water resources, but also the insecurity of the project, which is possible to lead social panic and bring threat to social harmony and stability.

Dam risk assessment and management in China has been studied and applied since the beginning of the twenty-first century (Li et al. 2015, 2018). In addition to considering the degree of safety of the project itself, risk management focuses on whether the potential threat caused by the dam exceeds the tolerable level of downstream residents. Its concept is more comprehensive and better reflects the relationship between engineering and people, engineering and society in a comprehensive and quantitative way, which is a more scientific and systematic management mode (Li et al. 2018). Therefore, it is especially important to accelerate the research and application of risk management methods and technology in the cascade reservoirs. Moreover, as an important management task, dam risk assessment should no longer be limited to a single reservoir, but needs to fully consider the adverse effects of upstream cascade dam breach on the downstream cascades, and clarify the transmission, blocking or amplifying effects of each cascade in the risk formation path, so as to systematically measure their actual risk status.

## 3 Research progress of risk assessment of cascade reservoir dams

The current studies on dam risk are still emerging, but most of them focus on general reservoirs that are independent of each other, while relatively few studies have been conducted on cascade reservoirs (Cai et al. 2019; Zhang et al. 2021b). Professor David Bowles put forward the concept of reservoir group risk analysis for the first time (Bowles 2000), whose purpose is mainly to provide owners with methods related to the safety management of reservoir cluster systems, as well as the flow of funds and the sequencing of reinforcement. In recent years, scholars have actively explored the risk of cascade reservoir dams from different aspects and achieved abundant results.

### 3.1 Physical model experiments on successive dam breaches in cascade reservoirs

Physical model experiments are one of the most important technical tools to study dam breach, especially when there is a lack of dam breach data and information, model experiments can be used as supplementary to provide validation for theoretical solutions and numerical simulations. Based on flume experiments, Takayama et al. (2021) expounded that the main influencing factors of flood peak of successive dam breaches are dam height, reservoir water level and the distance between two adjacent dams. By equipping the experimental model with high-precision pressure sensors, Chen et al. (2014) studied the pressure load exerted by dam-break flood on the downstream cascade dam, and proposed an empirical to predict the maximum pressure load. Tan et al. (2019) studied the evolution of the upstream breach flood in the downstream reservoir and the pre-dam creep height based on physical model experiments, they derived an empirical formula for the initial wave creep height value in front of the downstream dam and the degree of influence of various factors on the initial wave creep height. Cao et al. (2011) present an experimental and computational study on the flood flow induced by cascade landslide dam failure. In their study, the occurrence of streamwise progressive enhancement of the flood induced by cascade landslide dam failure was demonstrated. Li et al. (2013) simulated the successive dam-break flood based on orthogonal experimental method, it shown that the erosion rate and the origin water level of the downstream cascade had a strong influence on the successive dam-break analysis model. Zhang and Xu (2017) conducted flume experiments with cascade reservoirs to investigate the retarding effects of the intermediate intact dam on dam-break

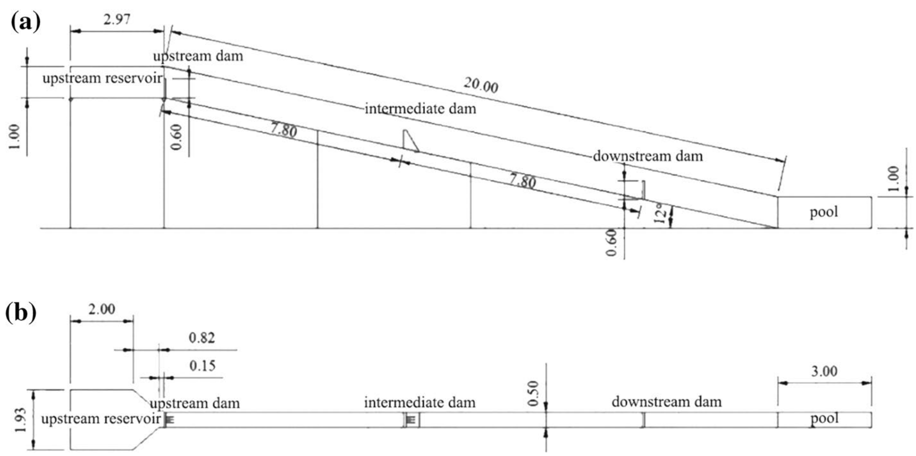



**Fig. 3** Dimensions (in m) of the experimental setup: **a** side view, **b** plan view

flow, as shown in Fig. 3, the results revealed that the retarding effects of the dam were primarily affected by the ratio of the water depth in front of the dam to the dam height.

Most of the above experimental studies focus on the quantitative relationship between the variable parameters and the dam breach indexes, aiming to acquire more scientific empirical formulas and numerical models, so as to provide a certain basis for building a more reasonable risk analysis and evaluation system (Chen et al. 2014; Tan et al. 2019). However, limited by the experimental conditions and the level of statistical technology, it has not been able to reveal the mechanisms of risk coupling and correlation among cascade reservoirs, which needs to be further deepened.

### 3.2 Numerical simulation of the dam-break flood of cascade reservoirs

In addition to physical model experiments, numerical simulation technology is also an important way to study the successive dam breaches in cascade reservoirs. Marche et al. (1997) described a simulation methodology that was developed to evaluate the impact of extreme floods and dam failures on cascade reservoirs. Combing a two-dimensional fully dynamic model, Dewals et al. (2011) developed a practical methodology for predicting flows generated by cascade dam breaches. Liu et al. (2019) evaluated the possibility of a cascade breach by developing a coupled breach-modeling platform based on one-dimensional flow modeling of the river channel, flood propagation and wave damping downstream. According to the three-dimensional Navier–Stokes equation and smoothed particle hydrodynamics theory, Luo et al. (2019) simulated the complicated dam-break flood flow and obtained its evolution characteristics in the downstream reservoir. Based on a dam breach simulation for three cascade reservoirs, Riha et al. (2020) studied the attenuation effect of dam-break peak discharge and presented that the attenuation of flood flow increased approximately exponentially with the distance from the dam site. By establishing a coupled shallow water hydrodynamic numerical model, Cao et al. simulate (2014) the failure of cascade landslide dams and clarified the streamwise progressive enhancement mechanism of dam-break flood. Hu et al. (2020) uses two models, BREACH and

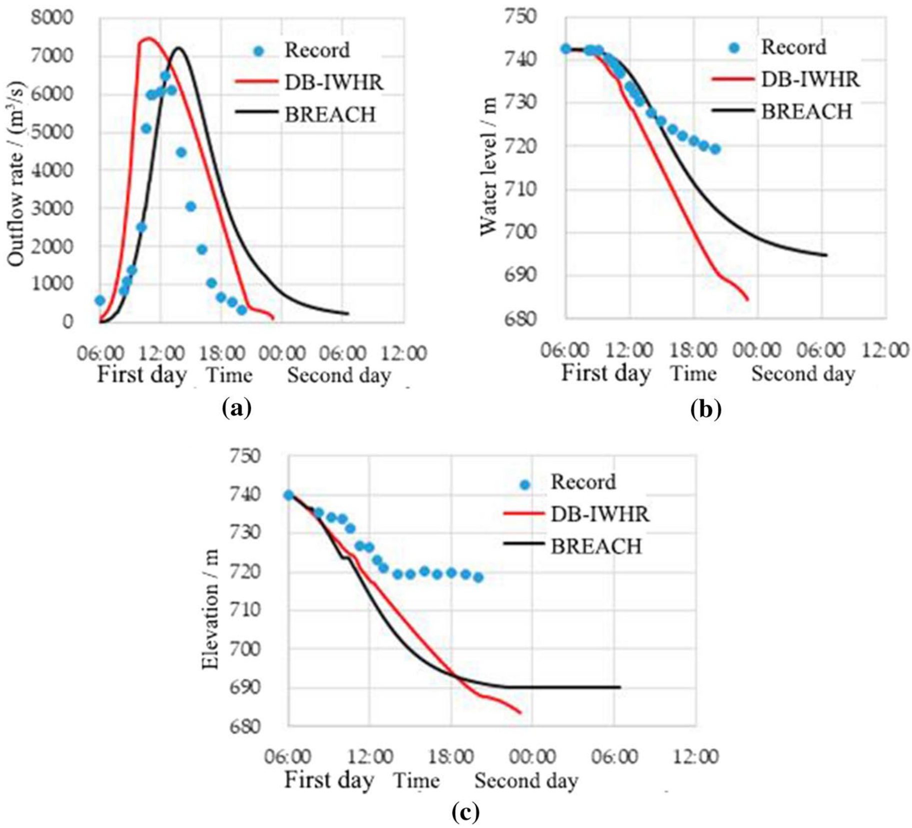



**Fig. 4** Comparison between the recorded data and the computed results of DB-IWHR and BREACH: **a** outflow rate of the dam-break flood; **b** water level in the breach; **c** breach bottom elevation

DB-IWHR, to carry out numerical simulation and risk assessment of dam breach in cascade reservoirs, as shown in Fig. 4.

The above study considered the diversity and complexity of the dam risk of cascade reservoirs, the continuous accumulation and improvement of numerical simulation theory also laid the foundation for further studies. With the improvement of software simulation technology, the accuracy and practicality of the obtained results have also been improved (Yang et al. 2018). However, specific dam breach scenarios or working conditions are mostly assumed in the simulation and risk analysis, without considering the uncertainty of their occurrence in combination with probability. Hence, these studies need to be improved to reasonably reflect the engineering reality.

### 3.3 Risk analysis and calculation of cascade reservoirs

Risk analysis and calculation are the basis and key to carry out risk assessment. In view of the risk characteristics of cascade reservoirs, Zhou et al. (2015a) introduced the causes, mechanism and successive breaches mode of cascading landslide dams, their results shown that the overtopping breach is the most important damage mechanism. Based on system

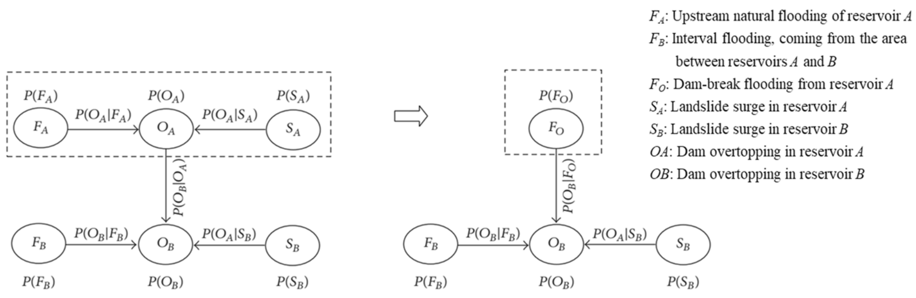



**Fig. 5** BN structures for two-reservoir breach in cascade reservoirs

engineering theory, Yang et al. (2016) constructed a risk analysis framework for a cascade reservoir system and predicted its brittle risk. Zhou et al. (2018) proposed that the engineering design of cascade reservoirs should fully consider the mutual influence among dams, and initially constructed a risk design method and control system for cascade reservoirs. Zhang et al. (2016) analyzed the upstream dam-break flood in the overtopping risk calculation and proposed a mathematical model to quantify the risk probability. Through the analysis of landslide under the combined action of flood and earthquake, Chen et al. (2017) explored the risk of earth rock dam in cascade reservoirs; Li and Liang (2016) constructed a constructed a Bayesian network (BN) model to deduce the probability of overtopping and evaluate the risk of successive dam breaches in cascade reservoirs, as shown in Fig. 5.

All of the above studies have noted the additional risk generated by the upstream cascade on the downstream cascade, although there was a lack of quantitative analysis of the risk transfer and superposition mechanism. Most of these studies focused on the risk analysis of unilateral factors (such as floods), but failed to carry out systematic analysis under the coupling of multiple factors. In addition, the risk factors faced by a single reservoir dam also act on cascade reservoir dams, and the risk probability calculation methods of a single reservoir dam have been widely used, which are meaningful to be extended and applied to cascade reservoir dams (Kalinina et al. 2018; Li et al. 2019; Rezaiee-Pajand et al. 2021). However, there is still no calculation concept and method that can effectively connect with them.

### 3.4 Risk consequence assessment of dam breach in cascade reservoirs

Compared with the safety management, the risk management model adds a focus on the consequences of risk accidents. Xu et al. (2014) constructed a risk loss index objective function and proposed that the loss calculation of a cascade reservoir breach should be combined with the probability of successive breaches of its downstream cascades. Yang et al. (2017) calculated the inundation process of a cascade reservoir dam-break flood in a downstream city, and pointed out that the inundation rate and maximum inundation area were mainly related to the maximum flow. Ge et al. (2021) divided the factors affecting the life loss of a dam breach into major and secondary factors, and analyzed their mechanism of action, respectively. Taking into consideration 20 factors, including hazards, exposure and vulnerability, Li et al. (2018) constructed a risk evaluation index system of the consequences of dam breach, as shown in Fig. 6.

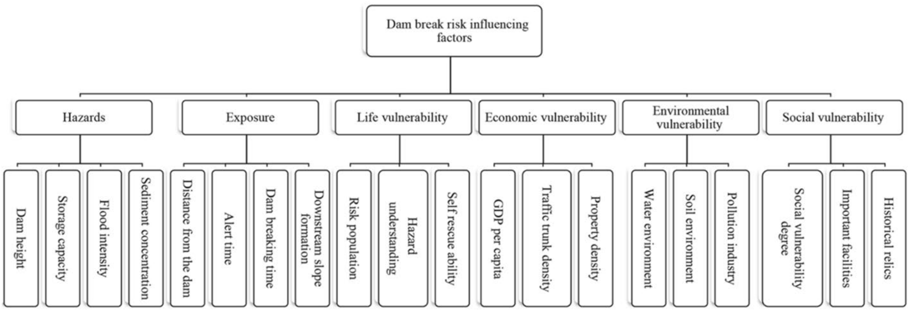



**Fig. 6** Index of influencing factors of dam breach risk consequences

Successive dam breaches analysis and flood routing calculation are not only the key to explore the risk correlation mechanism among cascade reservoirs, but also an important basis for evaluating the inundation losses under dam-break flood. However, most of the existing studies analyzed the dam breach consequence of cascade reservoirs by supposing a fixed successive dam breaches scenario, without considering the probability of its occurrence and the uncertainty of dam-break flood. In addition, the consequence caused by a dam breach in cascade reservoirs are often comprehensive. Thus, it will be of more practical significance to explore the comprehensive evaluation methods of various losses and establishing a relevant evaluation standard.

### 3.5 Risk criteria construction of cascade reservoirs in China

A scientific and reasonable risk criteria of cascade reservoirs is helpful to measure the risk level of each cascade from the perspective of the whole basin, so as to judge whether the risk of the project can be tolerated or accepted by the public. In view of the issue of uncoordinated flood control criteria, Wang et al. (2011) suggested that the downstream cascades should be considered as the protected objects of their upstream cascade, which provided a new view for the constitution of flood control criteria of cascade reservoirs. Zhou (2015a, 2015b) and Du (2015) established a risk rank criteria for cascade reservoirs in China. In their study, the risk prevention and control design method of "safety coefficient—reliability index—annual failure probability" was proposed, which preliminarily realized the quantitative conversion and comparison between dam safety criteria and risk criteria. Zhou et al. (2018) explored the safety criteria for cascade reservoirs and put forward the proposal to set up special projects. Wang et al. (2020) presented a construction method of safety criteria and risk criteria for cascade reservoirs in China based on data statistics and risk curve. Ge et al. (2020a, b) proposed a *P-P* curve that considered the annual dam failure probability, population at risk, and dam height, to establish societal life risk criteria for much higher dams, as shown in Fig. 7.

The risk criteria of cascade reservoirs should be able to comprehensively reflect the risk probability and consequences, which is systematic and holistic. Existing studies lack to construct risk standards in combination with national conditions and socio-economic development (Li et al. 2015; Ge et al. 2020a, b). In addition, the risk indicators, calculation methods and criteria have not been strictly uniform and correspond to each other, and need to be effectively connected with the current relevant norms and criteria.

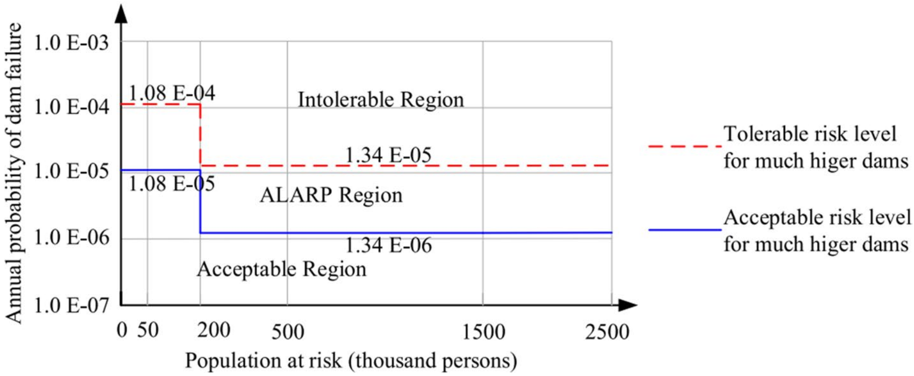



**Fig. 7** Risk criteria for much higher dams in China based on *P–P* curve (annual probability of dam failure population at risk)

# 4 Reflection and thoughts on risk assessment methods of cascade reservoirs

## 4.1 Overview and decomposition of dam risks of cascade reservoirs

In addition to natural flood, earthquake and other own risk factors, the dam in the cascade reservoirs is also suffered the additional risk transmitted from the upstream cascades, and its own breach will also have varying degrees of impact on the downstream cascades (Wang et al. 2022), as shown in Fig. 8.

To simplify the problem and make the sources of risk more intuitive, the authors have decomposed and defined the risk of cascade reservoir dams in their previous

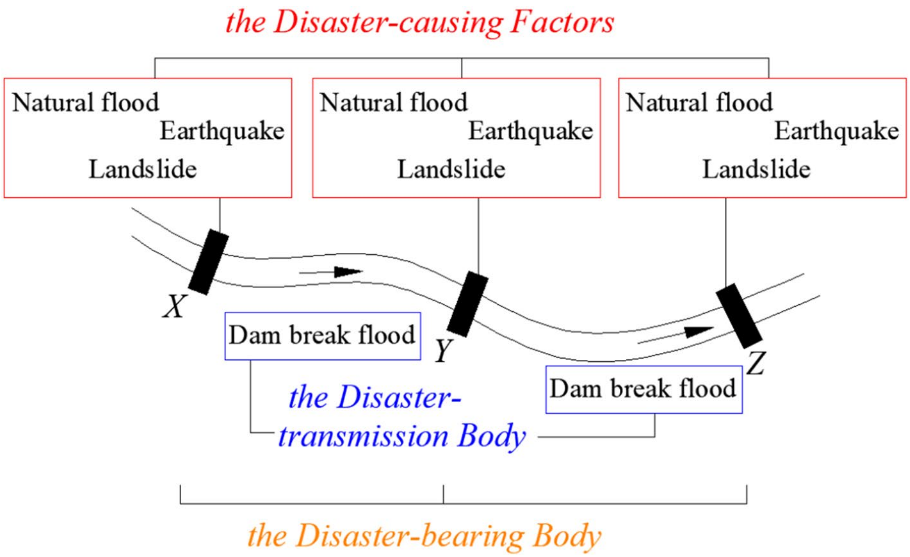



**Fig. 8** Risk analysis of cascade reservoir dams

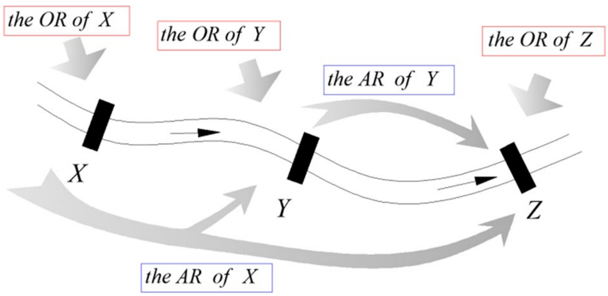



**Fig. 9** Decomposition of dam risk of cascade reservoirs

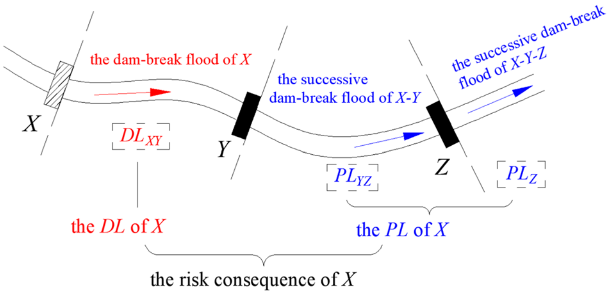



**Fig. 10** Decomposition of dam breach risk consequence of cascade reservoirs

research (Wang et al. 2022). For a cascade reservoir dam, the total risk is decomposed into its own risk (*OR*) and additional risk (*AR*). *OR* is defined as the dam breach probability under the action of its own risk factors, regardless of the effect of upstream cascades. Generally, *OR* mainly includes natural flood, earthquake, landslide and spill failures, which can be quantified through the calculation model of the dam breach probability for general reservoirs (Li et al. 2019; Wang et al. 2022). Besides, the cascade reservoir dam is additionally exposed to a portion of risk due to the possibility of dam breach in its upstream cascades, which is defined as the *AR*, as shown in Fig. 9.

Similarly, according to the impact scope of a cascade dam breach in its downstream area, the risk consequence is decomposed into direct loss (*DL*) and potential loss (*PL*), as shown in Fig. 10.

Dam *X* at the most upstream in Fig. 8 was taken as an example, if this cascade breaks, $DL_{XY}$ is its *DL*, which represents the loss caused by its dam-break flood in the segment between dams *X* and *Y*. No matter whether the downstream cascade breaks or not, this inundation loss is exist; in addition, the breach of dam *X* may also lead to the successive breaches of dams *Y* and *Z*. $PL_{YZ}$ and $PL_Z$ are the *PL*: the former represents the loss caused by the successive dam-break flood in the segment between dams *Y* and *Z*; the latter represents the loss caused by the successive dam-break flood in the downstream area of dam *Z*. The value of *PL* is determined by two indicators: the probability of successive breaches scenario and the inundation loss in the corresponding segment caused by dam-break flood.

### 4.2 Quantification of dam risk correlation of cascade reservoirs

The dams in cascade reservoirs are not independent of each other, but are interrelated, mainly manifested in risk transfer and superposition. As analyzed above, each dam bears

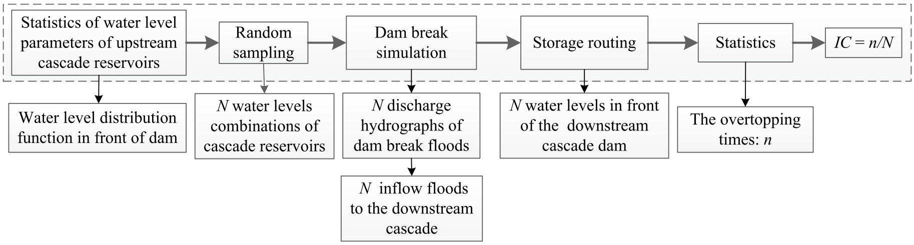



**Fig. 11** Calculation flow of *IC*

the risk transmitted from its upstream cascades and also brings certain risk to its downstream cascades. How to quantify the correlation of risk among the cascade dams is the key to calculate the risk probability and consequence of dam breach. The authors define an influence coefficient *IC* to reflect the degree of risk transmission and superposition. In fact, the result of risk transmission and superposition is the change of dam breach probability of downstream cascades. Therefore, the *IC* is further equivalent to the conditional probability that an upstream dam failure triggering a successive breach of its adjacent downstream dam, which range is [0,1] (Wang et al. 2022).

Since the trigger of successive dam breaches is the upstream dam break flood, the *IC* can be quantified by analyzing the effect of dam-break flood on the downstream cascade. Practice has shown that overtopping is the main breach mode of most dams, especially earth rock dams (Sun et al. 2012; Zhou et al. 2020). This study also takes overtopping of the downstream cascade dam as the criterion for successive breach caused by the upstream dam-break flood: once a cascade dam breach causes the overtopping of its downstream dam, it is considered to have caused a successive dam breach. In fact, the reservoir water level of each cascade reservoir during the operation period is fluctuating, a specific water level cannot represent all scenarios (Xiong et al. 2019; Zhou et al. 2014). For example, if the water level of the upstream cascade is high while the downstream is low, the downstream cascade may retain the upstream dam-break flood and avoid successive dam breaches. To be brief, the uncertainty of reservoir water-level combination determines the randomness of successive breaches. Therefore, the quantification of *IC* is based on random simulation and mathematical statistics (Wang et al. 2022). Through sampling different water-level combinations of upstream and downstream cascade reservoir, the dam-break simulation and storage routing are carried out (Chen et al. 2017; Wang et al. 2022). Ultimately, the frequency of successive breach is calculated and taken as the value of *IC*, as shown in Fig. 11.

## 4.3 Concept and method of dam risk assessment for cascade reservoirs

### 4.3.1 Calculation of dam risk probability

Risk probability is defined as the probability that a risk event will occur (Wang et al. 2022; Zhong et al. 2011). Taking the dam *X* at the most downstream in Fig. 9 as an example, its total risk contains the *OR*, as well as the *AR*s from dams *X* and *Y*. Therefore, the risk probability calculation method for dam *Z* is as follows.

$$P_Z = \mathrm{OR} + \mathrm{AR} = \mathrm{OR} + P_{YZ} + P_{XYZ} \tag{1}$$

where $P_{YZ}$ is the successive breaches probability of dams *Y* and *Z*, and $P_{XYZ}$ is the successive breaches probability of dams X, Y and Z.

According to Sect. 4.1, *AR* depends on both the dam breach probability of upstream cascade and the conditional probability of successive dam breach. Moreover, *IC* represents the conditional probability of the targeted dam breach caused by its upstream dam breach, $P_{YZ}$ and $P_{XYZ}$ can be further decomposed, as shown in Eq. (2).

$$\begin{cases} P_{YZ} = P_Y \times I_{YZ} \\ P_{XYZ} = P_X \times I_{XY} \times I_{XYZ} \end{cases} \tag{2}$$

where $P_Y$ and $P_X$ are the total risk probabilities of dams *Y* and *X*, respectively; their calculation idea of them is the same as $P_Z$, which can be obtained by iterative operation using Eq. (1) and (2); $I_{YZ}$, $I_{MN}$ and $I_{XYZ}$ are the *IC*s, which, respectively, represent the conditional probability of *Y–Z* successive breach caused by dam *Y*, the conditional probability of *X–Y* successive breach caused by dam *X* and the conditional probability of *X–Y-Z* successive breach caused by *X–Y* successive breach.

By substituting Eq. (2) into Eq. (1), the total risk probability of dam *Z* in the cascade reservoir system is obtained, as shown in Eq. (3).

$$P_Z = \mathrm{OR} + \mathrm{AR} = \mathrm{OR} + P_Y I_{YZ} + P_X I_{XY} I_{XYZ} \tag{3}$$

### 4.3.2 Risk consequence assessment of dam breach

Risk consequence is defined as the possible impact and loss caused by a risk event (Li et al. 2018; Ge et al. 2022). Taking the dam *X* at the most upstream in Fig. 10 as an example, its own breach will produce *DL* in the segment between dams *X* and *Y*. In addition, it may also lead to the downstream dam *Y* breach (*X–Y* successive breach) and dam *Z* breach (*X–Y-Z* successive breach), with corresponding *PL*s in corresponding segments. Because of the uncertainty of successive dam breach, the segment losses are multiplied with the *IC*s. Thus, the calculation method of dam breach risk consequence of dam *X* is shown in Eq. (3).

$$C_X = \mathrm{DL} + \mathrm{PL} = L_{XY} + \mathrm{PL}_{YZ} + PL_Z \tag{4}$$

where $C_X$ is the total risk consequence of dam *X*, which mainly includes loss of life, economic loss and environmental impact (Ge et al. 2021; Li et al. 2018). $L_{XY}$ is the loss caused by dam *X* breach in the segment between *X* and *Y*. Combined with the definition of *IC* and *PL*, the $PL_{YZ}$ and $PL_Z$ can be further decomposed, as shown in Eq. (5).

$$\begin{cases} \mathrm{PL}_{YZ} = I_{XY} \times L_{YZ} \\ \mathrm{PL}_Z = I_{XY} \times I_{XYZ} \times L_Z \end{cases} \tag{5}$$

where $L_{YZ}$ is the loss caused by the successive dam breach of *X–Y* in the segment between *Y* and *Z*. $L_Z$ is the loss caused by the successive dam breach of *X–Y−Z* in the downstream area of dam *Z*.

These segmented losses can be calculated according to the evaluation method of flood inundation loss (Alvarez and Alonso 2018; Ge et al. 2021; Pisaniello and Tingey-Holyoak, 2017). By substituting Eq. (5) into Eq. (4), the total risk consequence of dam *X* is obtained, as shown in Eq. (6).

$$C_X = L_{XY} + I_{XY}L_{YZ} + I_{XY}I_{XYZ}L_Z \tag{6}$$

#### 4.3.3 Classification of the project rank considering dam risk

With the rapid development of cascade reservoir construction, the scale of cascade reservoir group is also increasing (Cai et al. 2019; Fan et al. 2015). Therefore, it is necessary to reasonably determine the project rank of each cascade reservoir to realize differentiated management and formulate corresponding risk prevention. In view of the importance of cascade reservoirs in social and economic development and the complexity of risk consequence, their classification should not only consider the relevant provisions of a single reservoir, but also the risk transmission and superposition effects in their risk analysis. The index system of different countries can be constructed according to national conditions and relevant policies. Here, the research on the classification method for cascade reservoirs in China is taken as an example for specific analysis.

According to the scale, benefits, and the importance to the national economy, the water and hydropower projects in China are classified into five ranks, as shown in Table 1. It can be seen that the scale of the project and efficiency indicators are emphasizes quantitatively and specifically, while the protected objects, which can reflect the consequences of dam breach to a certain extent, are considered qualitatively and ambiguously (Ge et al. 2020a, b; Ren et al. 2017). In addition, this standard is mainly for general reservoirs, and its applicability to cascade reservoirs needs to be demonstrated.

Although the current project rank classification standard method of China cannot be directly applicable to cascade reservoirs, its consideration of engineering scale and downstream protection objects can lay a foundation for the classification of cascade reservoirs. Among the benefit indicators in Table 1, the two main ones that can be applied to cascade reservoir are "Flood control" and "Power generation" (Fan et al. 2015; Liu et al. 2021). The "Power generation" is still determined through installed capacity, while the "Flood control" is difficult to measure due to the risk transmission and superposition in cascade reservoir group. Considering this limitations, the risk consequence of a cascade dam breach, that is, various inundation losses considering risk transmission and superposition effect, can be taken as the quantitative value of its protected objects of flood control to determine the project rank. For example, if the farmland inundation area directly caused by the dam breach of a cascade reservoir is 100 $Km^2$, and this breach has a 10% probability of causing the successive dam breach of its downstream cascade, resulting in another farmland inundation of 1,000 $Km^2$, then it is considered that the protected farmland area of the cascade reservoir is 200 $Km^2$ ($C = 100 + 10\% \times 1000$) according to Eq. 6.

In addition, in order to reflect the consequence of dam break more comprehensively, the "Expected loss" is added into the current standard as the risk indicator, and "Population at risk" and "Equivalent economic scale" are introduced as its secondary indicators (Ge et al. 2021). Ultimately, a standard for rank classification of cascade reservoir integrating scale, benefits and risk consequence is proposed, as shown in Table 2. Adding the risk indicator into the classification standard is of great significance for the practical application of the dam risk management concept, which is helpful for the management department to control the risk, so as to ensure the safety of the basin.

**Table 1** Standard for rank classification of water and hydropower projects in China

| Project rank | Reservoir class | Capacity (Million $m^3$) | Flood control | | Waterlog Control | Irrigation | Water Supply | Power generation |
|---|---|---|---|---|---|---|---|---|
| | | | The importance of the protected cities | Area of the protected farmland ($Km^2$) | Waterlog Control Area ($Km^2$) | Irrigation Area ($Km^2$) | Importance of Water Supplying Object | Installed capacity ($10^4$kw) |
| I | Large (1) type | [1000, ∞) | Particularly important | [3333, ∞) | [1333, ∞) | [1000, ∞) | Particularly important | [120, ∞) |
| II | Large (2) type | [100, 1000) | Important | [667, 3333) | [400, 1333) | [334, 100) | Important | [120, 30) |
| III | Medium type | [10, 100) | Moderate | [200, 6667) | [100, 400) | [33, 334) | Moderate | [5, 30) |
| IV | Small (1) type | [1, 10) | General | [33, 200) | [20, 100) | [3, 33) | General | [1, 5) |
| V | Small (2) type | [0.1, 1) | | [0, 33) | [0, 2) | [0, 3) | | [0, 1) |

**Table 2** Standard for rank classification of cascade reservoir group project based on current standard and risk analysis

| Project rank | Reservoir class | Capacity (Million $m^3$) | Flood control | | Power generation | Expected loss | |
|---|---|---|---|---|---|---|---|
| | | | The importance of the protected cities | Area of the protected farmland ($Km^2$) | Installed capacity ($10^4$kw) | Population at risk (thousand persons) | Equivalent economic scale (thousand persons) |
| I | Large (1) type | [1000, ∞) | Particularly important | [3333, ∞) | [120, ∞) | [1500, ∞) | [3000, ∞) |
| II | Large (2) type | [100,1000) | Important | [667,3333) | [120, 30) | [500, 1500) | [1000, 3000) |
| III | Medium type | [10, 100) | Moderate | [200,6667) | [5, 30) | [200, 500) | [400, 1000) |
| IV | Small (1) type | [1, 10) | General | [33, 200) | [1, 5) | [50, 200) | [100, 400) |
| V | Small (2) type | [0.1, 1) | | [0, 33) | [0, 1) | [0, 50) | [0, 100) |

where "Population at risk" refers to all persons directly exposed to a certain depth of flood in the dam-break flood inundation area; "Equivalent economic scale " is the product of the per capita GDP index and the population at risk

## 5 Discussion

From the literature review, it can be seen that researchers have actively explored and achieved preliminary results in the dam risk assessment and management of cascade reservoirs. However, the interaction between upstream and downstream reservoirs, as well as the risk transmission and superposition mechanism, have been over-simplified, resulting in a large gap between research results and engineering practice. The simulation and analysis of successive dam breaches still focus on the study of breach development and flood routing, and less on the assessment of the probabilities and consequences of successive dam breaches from a macro perspective.

Specifically, the dam management mode in China still favors the traditional safety concept, which proposes safety standards by adjusting the relevant safety coefficients or reliability indexes (Li et al. 2015; Zhou et al. 2018) and does not sufficiently consider the severity of the consequences of successive dam breaches in the rank classification and risk criteria construction for cascade reservoirs. Most of the relevant theories and results are limited to a certain aspect, and a unified system of risk probability, risk consequences and corresponding criteria have not been formed yet, which needs to be further explored and verified in application. Therefore, it can be seen that the research on dam risk assessment of cascade reservoirs in China is still in the concept formation stage (Wang et al. 2022; Zhou et al. 2018).

The risk decomposition method proposed in this study can effectively connect the risk assessment method of cascade reservoir dams with that of a single reservoir dam. As described, the *OR*s of cascade reservoir dams can be calculated according to the traditional risk calculation method of a single reservoir dam (Ge et al. 2021; Kalinina et al. 2018; Li et al. 2019), its risk analysis is no longer limited to the unilateral risk source of flood, but can more comprehensively consider the impact of various risk factors. Moreover, the risk source and the impact scope of a cascade dam breach becomes clear and intuitive, which lays a foundation for the quantification of risk correlation (Wang et al. 2022).

Due to the huge system and complex risks of cascade reservoir, it is unreasonable to determine their project ranks directly according to the rank classification standard for general water conservancy and hydropower projects. As a supplement, the project rank classification method for cascade reservoirs proposed in this study takes into account not only the reservoir scale and benefits in socioeconomic development, but also the successive dam breach possibility and consequences, which is more scientific to provide guidance for engineering management.

## 6 Conclusions

Cascade reservoirs have brought benefits in flood control and resource utilization of the basin. However, once a cascade dam breaks, it will bring great pressure on the flood control of downstream cascade reservoirs, which is possible to lead to successive dam breaches and cause serious losses. The traditional dam risk assessment method of a single reservoir cannot meet the needs of practical problem analysis in cascade reservoirs. This paper analyses the current development status and risk management of cascade reservoirs in China, and review the relevant research progress. In view of the limitations of the existing studies, some concepts and methods for dam risk assessment and project rank classification of cascade reservoirs are put forward, which can provide reference for the further exploration and improvement of dam risk management. It is suggested that the following issues should be paid more attention in future theoretical research and engineering practice:

a. Accelerate the exploration of risk analysis and quantification methods for cascade reservoir group. Whether in risk probability calculation or risk consequence assessment, the uncertainty of risk factors will have a great impact on the final results. Therefore, proposing a method for quantifying the dam risk of cascade reservoirs under multiple uncertainties, which is both a prerequisite for risk analysis and a basis for accurately predicting the risk probability and consequences of dam breach, has become a key scientific problem to be solved.
b. Pay attention to the quantitative research on the risk correlation among cascade reservoir dams. The mechanism of risk induction, transmission and evolution among cascade reservoirs is extremely complex, which has not been fully revealed in the existing studies. Therefore, the research on the failure mode and mechanism of downstream cascade reservoir dams under the action of upstream dam-break flood should be a focus in future study. In addition, a method for analyzing the transmission, amplification or blocking role of each cascade reservoir unit in the cascade reservoir group should be proposed, so as to provide a basis for the risk prevention and the formulation of targeted risk management measures.
c. Build a risk assessment system in which risk probability, risk consequence and risk standard are unified with each other. Correspondingly, the risk probability is used to identify the weak units in the cascade reservoirs system, the risk consequence is used as the basis for measuring the severity of dam failure and formulating the emergency plan, and the risk standard is used to measure the dam risk level of each cascade reservoir.
d. Deepen the project rank classification method of cascade reservoirs based on risk analysis. Through the classification of project ranks, the differential management of reservoir dams can be realized to ensure the efficient utilization of resources. This paper puts forward the concept of supplementing the "Expected loss" into the current project rank classification standard of reservoir, but it still needs further in-depth studies to reflect the correlation of risks among cascade reservoirs in a more scientific way and make the quantitative calculation of each classification index more accurate.
e. Strengthen the practical application of risk management concept and technology in cascade reservoirs. At present, the cascade reservoir group projects in China include planning, construction in progress and built projects, involving multiple stages such as design, construction and operation, which provides a good platform for the promotion and application of risk management concepts and technologies. Accordingly, the studies should be closely integrated with the actual engineering practice to continuously improve the scientific and practicality of the theories and technologies related to risk management.

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## Declarations

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

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