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ABSTRACT

Cascade reservoirs are essential in water resource utilization, flood control, and disaster mitigation. They have been built in several rivers worldwide. The rank classification for cascade reservoirs has significant practical implications for resource distribution decisions and risk management strategies and is also essential for ensuring the security of the basin. Internationally, reservoirs are typically classified based on project scale and dam failure consequences, whereas the risk transmission and superposition effect renders the classification method of reservoirs not directly applicable to cascade reservoirs. Therefore, to address this issue, this study proposed a rank classification method for cascade reservoirs. First, based on the scale, benefits, and risk consequences of dam failure, an index system for the rank classification of cascade reservoirs was established. Second, by constructing social risk criteria for cascade reservoirs and establishing a link among "project rank-reliability index-annual failure probability," the allowable dam failure losses for different project ranks were determined. Thereafter, considering risk transmission and superposition, the rank classification standard and index quantification method for cascade reservoirs were proposed. Finally, five cascade reservoirs were selected for a feasibility study. The proposed method provides a supplement to the current rank classification standard of water conservancy projects in China and can also serve as a reference for risk assessment and classification management of cascade reservoirs in other countries.

1. Introduction

To utilize hydro energy resources, cascade development has been employed in several rivers worldwide, such as the Tennessee River in the United States, Yenisei River in Russia, Rhone River in France, Columbia River flowing through Canada and the United States, and Yangtze River and Yellow River in China (Bai et al., 2019; Latrubesse et al., 2017; Wang et al., 2023a). With the continuous development in construction technology and the growing demand for sustainable energy, the size of cascade reservoirs is also growing. This poses a significant challenge to the overall management of basins (Faucheux et al., 2022). Given the difference in scale, mission, and importance relative to the entire basin, there is an urgent need to study methods of rank classification for cascade reservoirs. This will allow for differential management and ensure the efficient distribution of limited resources (Wang et al., 2020).

Most countries worldwide classify reservoir projects based on their geometry (reservoir capacity and dam height), consequences of dam failure, or a combination of both, implementing various standards for design, construction, and operational management (Ren et al., 2017; Sheng and Fu, 2010). Through dam classification, regulation responsibility is assigned to different agencies to realize differentiated management. In the operation stage, dams with the most serious risk consequences are given specific attention and are usually directly supervised by the government to ensure their safety, as shown in Fig. 1.

Recently, dam failures have occasionally occurred with global climate change and the frequent occurrence of extreme weather events (Wu et al., 2021; Zhang et al., 2021). Compared with those in individual reservoirs, the risks in cascade reservoirs have transmission and superposition effects. The failure of a single dam in a cascade reservoir system may have severe consequences, potentially leading to failures of

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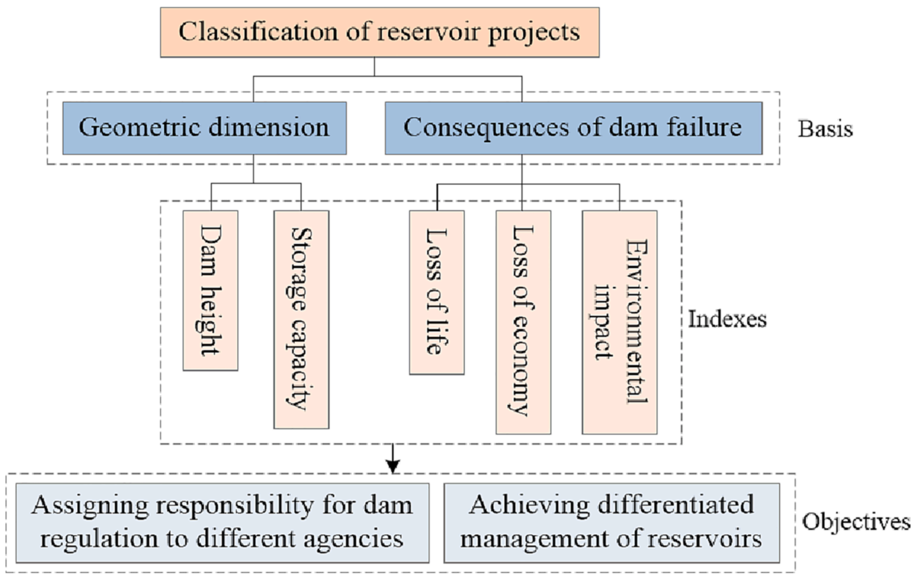


Fig. 1. Classification methods and objectives of reservoir projects.

Table 1
Classification indexes of reservoir projects in selected countries.

Country	Basis	Index
the United States of America	Project scale and dam failure consequences	Dam height, Storage capacity, Loss of life, Loss of economy and Environmental impact
Russia	Structure and dam failure consequences	Dam type, Dam foundation, Dam height and Loss of dam failure
Britain	Dam failure consequences	Loss of life, Loss of economy
Canada	Project scale and dam failure consequences	Dam height, Storage capacity, Loss of life, Population at risk, Loss of economy and Environmental impact
Australia	Dam failure consequences	Loss of life, Population at risk
France	Project scale	Reservoir capacity, Dam height
Germany	Project scale	Reservoir capacity, Dam height
India	Project scale	Reservoir capacity, Water head
China	Project scale and benefits	Reservoir capacity, Flood control, Water supply, and Power generation benefits

downstream reservoirs (Wang et al., 2023a,b; Mehta et al., 2020). With the rolling development of basins and the increased risk awareness of the public, the risk consequences of cascade reservoirs have become a public safety concern and should be considered in project rank classification.

The rank classification of water and hydropower projects follows the laws of nature and economy, involving the comprehensive coordination of several aspects such as technology, economy, safety, environmental protection, navigation, and society (Sheng and Fu, 2010; Li et al., 2021). Table 1 lists the classification indexes used in several countries (Ren et al., 2017). Among these indexes, scale and effects are currently used as the primary bases for classifying water and hydropower projects in China. The reservoir projects are classified into five ranks (I, II, III, IV, and V) based on scale and benefits. The permanent hydraulic structures are classified into five grades (1, 2, 3, 4, and 5) based on their importance and project rank (The Ministry of Water Resources of the People's Republic of China, 2017).

The classification methods in most countries are primarily intended for individual reservoirs and cannot be applied directly to cascade reservoirs. For instance, the current classification standard for water conservancy and hydropower projects in China states that the determination of project ranks and flood standards for cascade reservoirs should be subject to special analysis and demonstration (The Ministry of Water Resources of the People's Republic of China, 2017). Currently, the management of reservoir dams is transiting from safety to risk management, and research results on the risk of individual dams are being applied in practical applications of engineering (Escuder-Bueno et al., 2016). Contrarily, the risk issues of cascade reservoirs are extremely challenging, and related studies are still in the initial stage (Wang et al., 2023a). Regarding risk quantification and classification of cascade reservoirs, Lima et al. (2022) adopted a simplified method considering dam height, storage capacity, and potential risk to classify small dams in a cascade basin in Brazil. Ghimire and Schulenberg (2022) conducted a failure risk analysis of two cascading dams in Michigan, and evaluated the impacts of climate change on earthen dams. Based on multi-objective evolutionary algorithms and risk analysis methods, Manikkuwahandi and Hornberger (2021) proposed the operation rules for cascade reservoirs to enhance hydropower and agriculture yield. Micovic et al. (2016) presented stochastic simulation of floods on a cascade system of three dams and analyzed the causes of the risk of dam overtopping. Dewals et al. (2011) simulated the flood propagation and inundation process of successive dam failures. Wang et al. (2022) presented a method to calculate the risk probabilities of cascade reservoirs. Zhou et al. (2015) initially investigated the safety standards for cascade reservoirs based on the risk analysis of successive dam failures. Wang et al. (2020) conducted a targeted analysis and demonstration on the selection of relevant parameters of risk criteria for cascade reservoirs in China. The aforementioned studies have considered the complexity of the risk in cascade reservoirs, and their results serve as valuable sources for risk prevention and control. However, most existing studies focus on the evaluation of risk levels and the severity of dam failure consequences and therefore cannot support the comprehensive issue of rank classification for cascade reservoirs. In addition, index selection, quantification, and implementation standard have not been unified and need to be adequately integrated with existing regulations (Wang et al., 2023a).

Owing to the significance of water resources in social development and the consequences of dam failure, risk considerations should be incorporated into the rank classification of cascade reservoirs based on existing standards for general reservoirs. Therefore, this study proposed a rank classification method that comprehensively considered the project scale, benefits, and risk consequences of dam failure, providing a basis for the construction planning and risk management of cascade reservoirs.

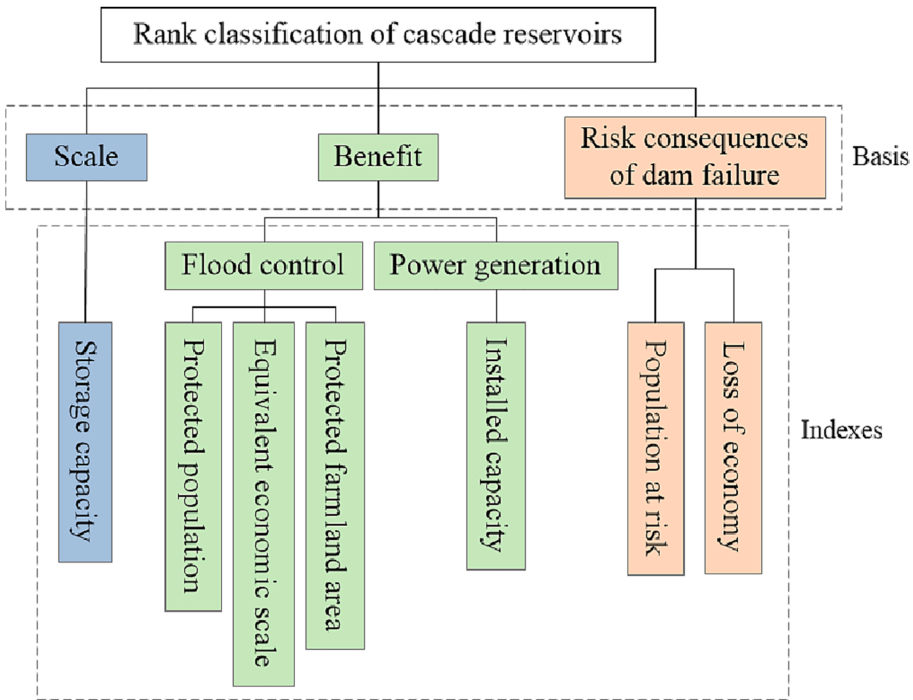


Fig. 2. Index system for the rank classification of cascade reservoirs.

2. Methods

The rank classification method for cascade reservoirs proposed in this study primarily includes the selection, threshold value determination, and quantification of indexes. Among them, the selection of indexes is based on the synthesis of reservoir classification methods used in different countries. Quantification focuses on the analysis of risk transmission and superposition effect, which are the differences between cascade and individual reservoirs. These two aspects are common in different countries. In contrast, the index thresholds in the rank classification standard are dependent on the level of social development and the risk tolerance of the public, and thus may vary across different countries (Ge et al., 2017; Ren et al., 2017). The index thresholds in this study are determined based on a specific analysis of cascade reservoirs in China, serving as a demonstration.

2.1. Construction of the index system for the rank classification of cascade reservoirs

As presented in Table 1, most European and American countries, especially economically developed countries, use scale and dam failure consequences as the primary bases for classifying reservoir projects. The project scale reflects the technical challenges of construction to a certain extent, whereas the consequences of dam failure cover specific considerations of potential risks caused by dam failure and are an important basis for determining engineering design and operation management standards (Li et al., 2018). In addition, as an essential reference for the normal function of water and hydropower projects, comprehensive benefits reflect their contribution and importance in the development of the national economy and should also be used as one of the classification bases (Lu et al., 2018; Rashid et al., 2018). Therefore, the scale, benefits, and risk consequences of dam failure are selected as the bases for the rank classification of cascade reservoirs.

Generally, the scale of a reservoir is reflected by two indexes: dam height and storage capacity. Notably, the project rank determined by dam height is lower than that determined by storage capacity, with the latter being more practical (Sheng and Fu, 2010). In addition, the risk consequences of dam failure have been listed separately as the bases for rank classification. Therefore, the storage capacity and dam height of a reservoir need not be combined to measure the severity of its dam failure. Regarding the current standard in China, the storage capacity is used as the scale index for rank classification (The Ministry of Water Resources of the People's Republic of China, 2017).

For the benefit indexes, cascade reservoirs primarily focus on disaster prevention and water resource conversion. The benefits of flood control and power generation are noticeable and are used as primary benefits indexes to classify project ranks (Lu et al., 2018; Zhou et al., 2014). Specifically, flood control benefits include protected population (permanent population in the flood control protected area), equivalent economic scale (the product of the per capita GDP index and protected population), and protected farmland area, whereas power generation benefits are reflected by the installed capacity (Sharifi et al., 2021; Wang et al., 2023a; Zhou et al., 2018).

Risk consequences indexes are used to reflect and primarily classify the potential inundation losses caused by a cascade reservoir dam failure into two aspects: life and economy (Jonkman et al., 2010; Li et al., 2018). According to Table 1 and related literature (Ge et al., 2021; Ge et al., 2020a; Li et al., 2019a), both "Loss of life (*LOL*)" and "Population at risk (*PAR*)" can be used to quantify the impact of dam failure on life safety. In practical terms, *LOL* refers to the actual fatalities in the downstream area caused by a dam-break flood. It ignores the number of residents transferred and rescued in an emergency. (Ge et al., 2022; Zhu et al., 2021); *PAR* refers to all the population directly exposed to the flooded area. Notably, even if reservoir dam failure does not ultimately result in *LOL*, the emergency relocation and resettlement of *PAR* is often accompanied by a significant consumption of social resources and can have corresponding risk consequences. Therefore, *PAR* is selected in this study as an index to reflect the impact of a dam failure on the life safety of downstream residents. (Peng and Zhang, 2013). In addition, "Loss of economy"(*LOE*) is used to reflect the impact of dam failure on the national economy and represent the various types of losses directly measurable in monetary terms caused by a dam-break flood (Li et al., 2018; Zhu et al., 2020). Ultimately, *PAR* and *LOE* are selected as the secondary indexes of "Risk consequences." Fig. 2 shows the index system for the rank classification of cascade reservoirs.

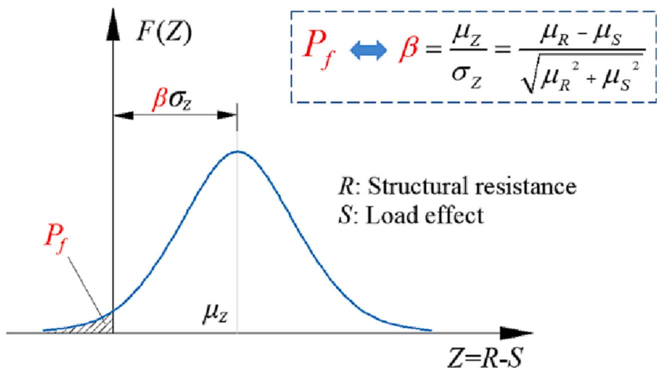


Fig. 3. Relationship between reliability index and failure probability.

2.2. Determination of the index thresholds

In addition to the index system, the determination of index thresholds corresponding to different project ranks is the key to constructing the rank classification standard. For a reservoir project, using extremely low index thresholds for classification will result in an extremely high project rank. Consequently, a considerable amount of human and financial resources needs to be invested to upgrade the required safety level to match the project rank, which is uneconomical (Li et al., 2019b; Lin et al., 2015). Conversely, using extremely high thresholds will lead to a low project rank, corresponding to a low-security requirement, and aggravates the risk borne by the downstream (Li et al., 2018).

The classification of the project rank of reservoirs according to scale and benefits has achieved wide application in China and formed a complete system (Ren et al., 2017). Therefore, the index thresholds of scale and benefits shown in Fig. 2 can continue to follow the relevant provisions in existing standards. For the indexes of risk consequences, their thresholds must be determined by considering the level of national economic development and the risk tolerance of the public.

Currently, the thresholds of *PAR* and *LOE* for different ranks of reservoir projects have not been defined in relevant technical standards. However, most countries and regions internationally reflect engineering safety through reliability indexes and have promulgated relevant technical standards, which specify the design service life and target reliability corresponding to different ranks of hydraulic structures (Hariri-Ardebili, 2018; Li et al., 2015a; McGuire and VandenBerge, 2017). Generally, the higher the project rank, the higher is the reliability indexes specified for the structures and the lower the failure probability.

According to the reliability theory, if the random variables of a structure obey normal distributions and their limit state equations are linear, a correspondence exists between the reliability index β and failure probability P_f (Ge et al., 2017; Li et al., 2015a; Wilde and Johansson, 2013; Zhu and Tang, 2023), as shown in Fig. 3 and Eq. (1).

$$Pf = P(Z < 0) = \int_{-\infty}^{0} f(Z)dZ = \Phi(-\frac{\mu Z}{\sigma Z}) \tag{1}$$

where Φ is the cumulative distribution function of standard normal distribution. When $Z = 0$, the $Z = R\text{-}S$ is referred to as the limit state equation, where R and S are set in a linear relationship (Shao et al., 2020; Wilde and Johansson, 2013).

It has been observed from monitoring data that a majority of random variable loads follow a normal or nearly normal distribution (Shao et al., 2020; Pereira et al., 2018; Wilde and Johansson, 2013). Notably, random variables that are not normally distributed can also be transformed to conform to a normal distribution by utilizing equivalent normalization or equal probability transformation (Shao et al., 2020). Therefore, the transformation between the reliability index and failure probability should be achieved based on the above-mentioned settings. Moreover, studies on this issue have been conducted systematically, presenting tables of mutual correspondence between reliability and failure probability in the relevant results and specifications (Hariri-Ardebili, 2018; Li et al., 2015a; McGuire and VandenBerge, 2017).

Accordingly, the allowable dam failure probability for reservoirs of different ranks can be defined by establishing a link among "project rank-reliability index-annual failure probability." In addition, the social risk criteria for reservoir dams can effectively reflect the acceptable and tolerable consequences of dam failure for the public under different dam failure probabilities (Ge et al., 2017), whereby the thresholds of risk consequence indexes allowed for different ranks of reservoirs can be obtained, as shown in Fig. 4.

2.3. Formulation of social risk criteria for cascade reservoir dams

As shown in Fig. 4, the formulation of the social risk criteria for cascade reservoir dams is crucial for determining the index thresholds of risk consequences. The social risk criteria reflect the relationship between the loss in a given accident and its probability of occurrence and can be used to determine the consequences allowed by the public for dam failures with different probabilities (Wang et al., 2020; Ge et al., 2017). Generally, the ALARP principle and *F–N* curves are used to construct social risk criteria. The ALARP principle (Li et al., 2015b) divides the risk into three regions, namely intolerable, tolerable (ALARP region), and acceptable regions, through the tolerable risk level (TRL) and acceptable risk level (ARL). The *F–N* curve (Wang et al., 2020) represents the relationship between the number of fatalities *N* and its exceeding probability P_f expressed using Eq. (2).

$$Pf(N > x) = 1 - FN(x)\frac{C}{x^n} \tag{2}$$

where $F_N(x)$ is the probability distribution function of the number of losses per annum, signifying the probability of less than × losses per annum, n is the steepness of the limit line, and C is the constant that

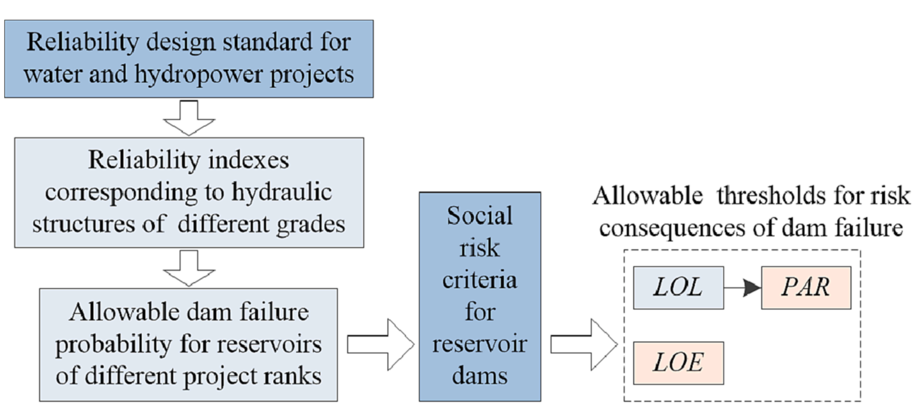


Fig. 4. Determination of the index thresholds of risk consequences.

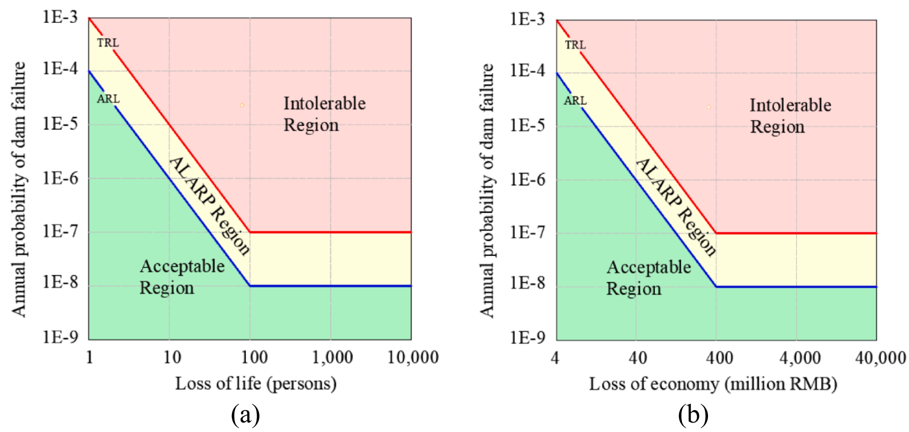


Fig. 5. Social risk criteria for cascade reservoir dams: (a) Loss of life; (b) Loss of economy.

Table 2
Annual failure probability corresponding to different project ranks.

Project rank	Hydraulic structure grade	Structure security grade	Design working life (Years)	Target reliability	Annual failure probability
I	1	I	100	4.2	1.33×10^{-7}
IIIII	23	II	100	3.7	1.08×10^{-6}
IVV	45	III	50	3.2	1.37×10^{-5}

determines the position of the limit line.

Li et al. (2015b) proposed social life risk criteria for reservoir dams in China. The TRL started at 10^{-2} and achieved an extreme value of 10^{-6}. The ARL started at 10^{-3} and achieved an extreme value of 10^{-7}. Given that a dam failure in cascade reservoirs may trigger successive dam failures in its downstream, cascade reservoir dams should have more demanding risk criteria than individual reservoir dams. Specifically, for social risk criteria, the dam failure probability of a cascade reservoir should be lower than that specified for an individual reservoir, corresponding to the same dam failure losses.

In our previous studies (Wang et al., 2023a; Wang et al., 2022), the total risk probability of a cascade reservoir dam was proposed to be equal to the sum of the weighted failure probabilities of its upstream dams and its failure probability. To ensure that the total risk probability of each dam in cascade reservoirs still satisfies the requirements of the social risk criteria for individual reservoir dams, the failure probability of a cascade reservoir dam should be one order of magnitude lower than that of an individual reservoir dam. Therefore, the TRL and ARL of cascade reservoir dams started at 10^{-3} and 10^{-4}, with 10^{-7} and 10^{-8} as the extremes, respectively; n is taken as 2, which represents an adverse risk preference (Li et al., 2015b). By using Eq. (2), the *LOL* corresponding to the inflection point at the lowest point of both the TRL and ARL is 100 persons, as shown in Fig. 5(a). In addition, the economic risk criteria are constructed regarding the ratio of one person corresponding to an economic loss of RMB 4 million (Ge et al., 2020c; Li et al., 2015b; Wang et al., 2020), as shown in Fig. 5(b).

As shown in Fig. 5, the relationships between the annual failure probability and the allowable consequences of cascade reservoir dams have been established. Based on these criteria, the loss threshold allowed by society under a certain dam failure probability can be obtained.

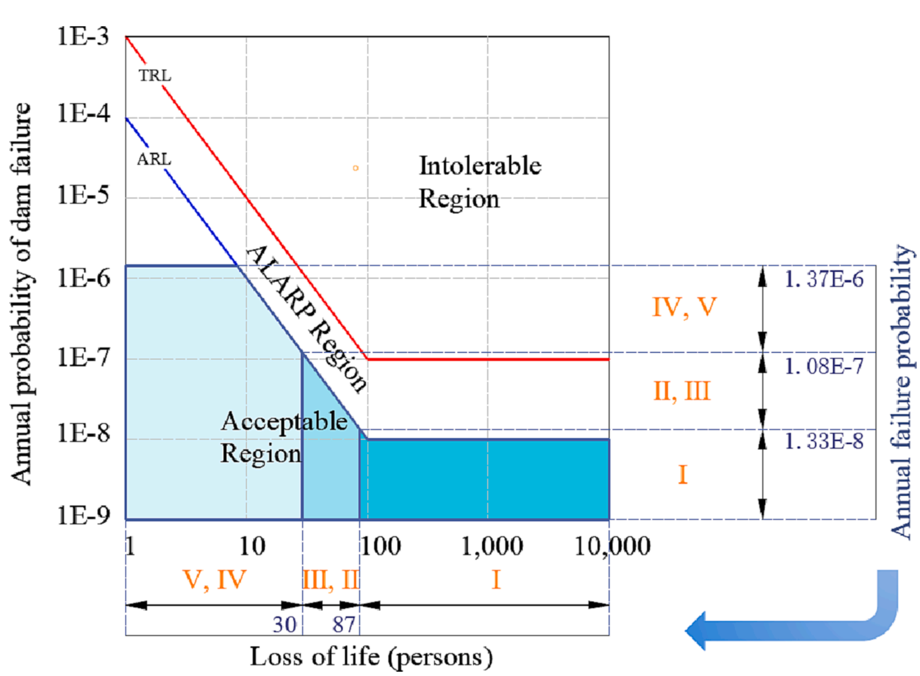


Fig. 6. Critical values of *LOL* corresponding to annual failure probabilities.

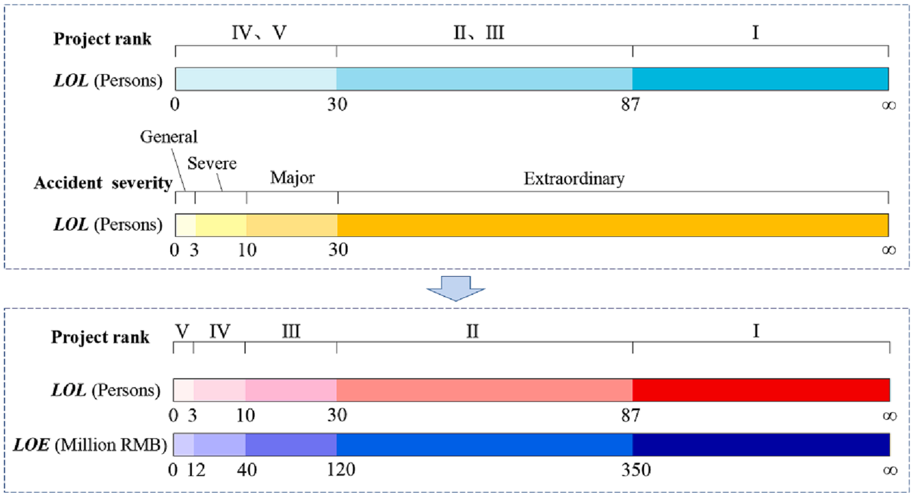


Fig. 7. Thresholds of dam failure losses corresponding to different project ranks.

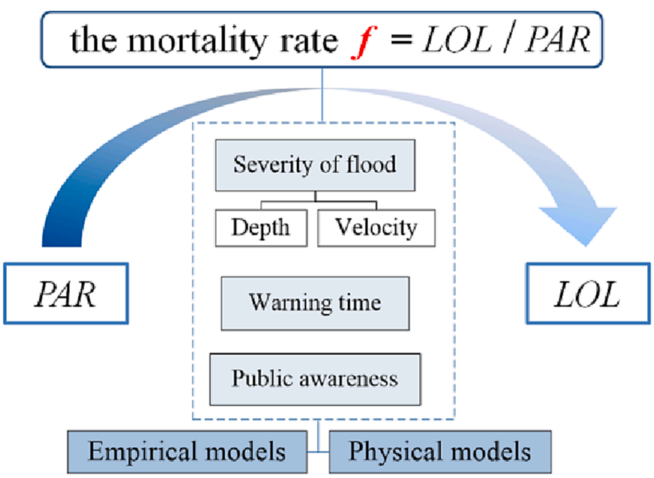


Fig. 8. Conversion between *PAR* and *LOL*.

2.4. Calculation of thresholds based on social risk criteria and reliable indexes

According to the structural safety grade, design service life, and target reliability of hydraulic structures at different grades specified in the Unified Standard for Reliability Design of Hydraulic Engineering Structures (GB50199-2013) in China, the allowable annual failure probabilities for different project ranks are calculated, as presented in Table 2. Notably, the annual failure probability in Table 2 is for individual reservoir dams, and the corresponding annual failure probability for cascade reservoir dams should also be reduced by one order of magnitude on this basis (Ge et al., 2020b; Li et al., 2015b). Considering the correspondence between the failure probability and acceptable losses in the social risk criteria, the critical values of the *LOL* corresponding to different failure probabilities are determined, as shown in Fig. 6.

Considering that the three threshold ranges shown in Fig. 6 are not sufficient for the classification of five project ranks, the accident classification standard in China is used as a reference to refine and divides the accident severity into four levels according to the *LOL* (Wang et al., 2020). Synthetically, the threshold values of the *LOL* corresponding to different project ranks are formulated. Among them, the failure of the Class V project corresponds to a general accident and the allowed *LOL* is less than three persons. The intervals of the *LOL* allowed for the other project ranks are sequentially extended and ensured to all following the upper limits allowed for each project rank in Fig. 6. In addition, the thresholds of *LOE* are determined on the ratio of one person responding to approximately RMB 4 million, as shown in Fig. 7.

Table 3
Thresholds of risk consequences for different project ranks.

Project rank	I	II	III	IV	V
Grade of hydraulic structure	1	2	3	4	5
PAR (persons)	[87/*f*, ∞)	[30/*f*, 87/*f*)	[10/*f*, 30/*f*)	[3/*f*, 10/*f*)	[0, 3/*f*)
LOE (million RMB)	[350, ∞)	[120, 350)	[40, 120)	[12, 40)	[0, 12)

The critical values of the *PAR* are determined according to its conversion relationship with the *LOL*, which can be established through the mortality rate of dam failure (Ge et al., 2022). Notably, the mortality rate f is closely related to flood severity, warning time, and public awareness of risk prevention, which are not invariable for different cases (Ge et al., 2021; Li et al., 2019a), as shown in Fig. 8. Therefore, the value of f is not specifically constrained but determined following the engineering reality in the specific application, as shown in Table 3.

In application, the *PAR* can often be rapidly quantified by combining the population density distribution and the simulated flood inundation range, whereas the *LOL* needs to be further deduced in combination with the mortality rate. Therefore, the *PAR* rather than the *LOL* should be used in the standard as a rank classification index from the perspective of promotion and application.

2.5. Risk consequences analysis and project rank classification of cascade reservoirs

The risk transmission and superposition among cascade reservoirs are primarily reflected in that the failure probability of a cascade reservoir dam is affected by the upstream cascades. In addition, its failure has varying degrees of impact on downstream cascades (Wang et al., 2023b). Based on the impact scope of a cascade reservoir dam failure in its downstream area, risk consequences are decomposed into direct consequences (*DC*) and potential consequences (*PC*), as shown in Fig. 8. Considering the failure of dam *M* shown in Fig. 9 as an example, its inundation area is segmented, and L_{MN} is the *DC* of dam *M*. Moreover, the failure of dam *M* has a certain probability to cause the successive dam failures of "*M*−*N*" and "*M*−*N*−*K*," further expanding the inundation losses. Consequently, PC_{NK} and PC_K are the *PC* of dam *M* and are not directly equivalent to the segmented losses L_{NK} and L_K because of the

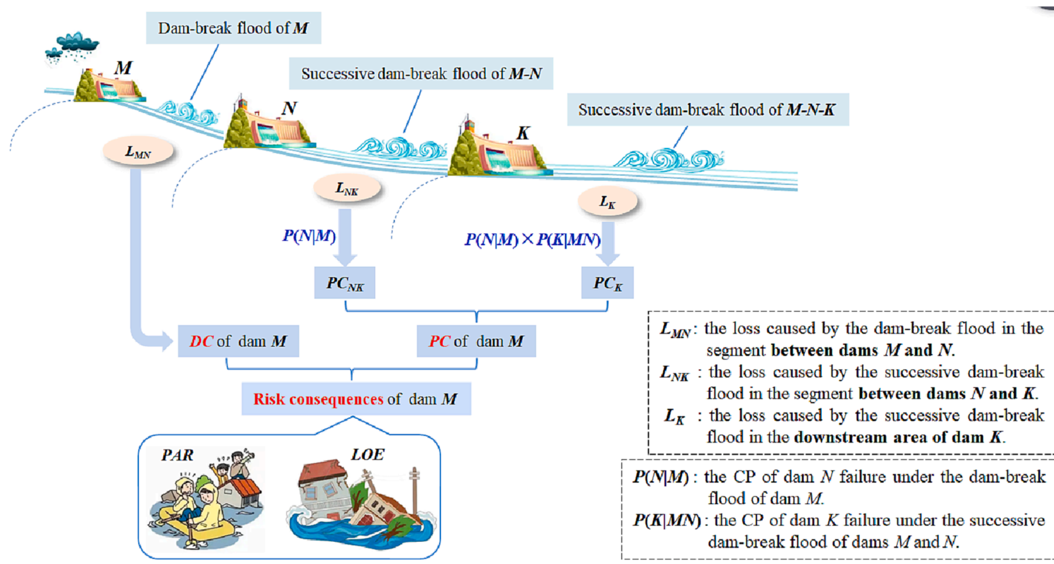


Fig. 9. Decomposition of dam failure risk consequences in cascade reservoirs.

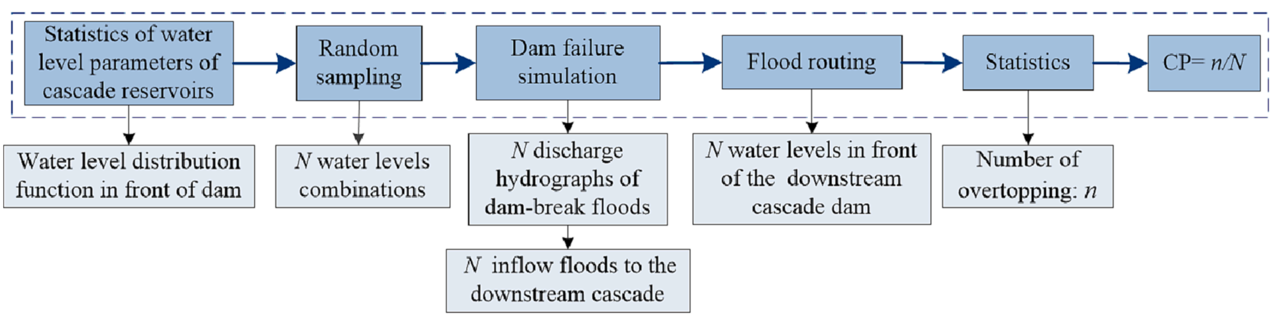


Fig. 10. Calculation of the CP of successive dam failure.

Table 4
Rank classification standard for cascade reservoirs in China.

Project rank	Scale	Benefits				Risk consequences	
	Storage capacity (million m^3)	Flood control Protected population (thousand persons)	Equivalent economic scale (thousand persons)	Area of the protected farmland (10^{3}km^2)	Power generation Installed capacity (10^{4}kw)	*PAR* (persons)	*LOE* (million RMB)
I	[1000, ∞)	[1500, ∞)	[3000, ∞)	[3333, ∞)	[120, ∞)	[87/*f*, ∞)	[350, ∞)
II	[100, 1000)	[500, 1500)	[1000, 3000)	[667, 3333)	[120, 30)	[30/*f*, 87/*f*)	[120, 350)
III	[10, 100)	[200, 500)	[400, 1000)	[200, 6667)	[5, 30)	[10/*f*, 30/*f*)	[40, 120)
IV	[1, 10)	[50, 200)	[100, 400)	[33, 200)	[1, 5)	[3/*f*, 10/*f*)	[12, 40)
V	[0.1, 1)	[0, 50)	[0, 100)	[0, 33)	[0, 1)	[0, 3/*f*)	[0, 12)

probabilistic nature of successive dam failures.

In our previous studies (Wang et al., 2023a; Wang et al., 2022; Wang et al., 2023b), the degree of risk transmission and superposition among cascade reservoirs was reflected by the conditional probability (CP) of downstream dam failure under an upstream dam-break flood. Through sample simulation and statistics, the frequency of the downstream dam overtopping was determined and used as the value of the CP, as shown in Fig. 10. Subsequently, the calculation method for dam failure risk consequences of the cascade reservoir (considering dam *M* shown in Fig. 9 as an example) was proposed, where *DC* was equal to the product of the CP of successive dam failure and segmented loss, as shown in Eq. (3).

$$CM = DC + PC = LMN + P(N|M) \times LNK + P(N|M) \times P(K|MN) \times LK \quad (3)$$

where C_M is the total risk consequence of dam M, which primarily includes *LOL*, *LOE*, and environmental impact.

Using the project scale, benefits, and risk consequences of dam failure, a standard for the rank classification of cascade reservoirs is constructed, as presented in Table 4. In application, the indexes of scale and

Table 5
Classification of the permanent structures of cascade reservoirs.

Project rank	Grade of hydraulic structure	
	Main structure	Secondary structure
I	1	3
II	2	3
III	3	4
IV	4	5
V	5	5

Table 6
Engineering parameters of the selected cascade reservoirs in the Hongshui River basin.

Reservoir	Total capacity (10^8 m^3)	Dam crest elevation (m)	Normal pool level (m)	Checking flood level (m)	Protected population (thousand persons)	Installed capacity (10^4kw)
Dahua	9.6	174.5	155	169.63	106	45.6
BLT	3.4	135	129	132	365	38.2
Letan	9.5	117	112	115	513	60
QG	2.3	86	84	86	427	48
DTX	34.8	64	61	63.9	2632	160

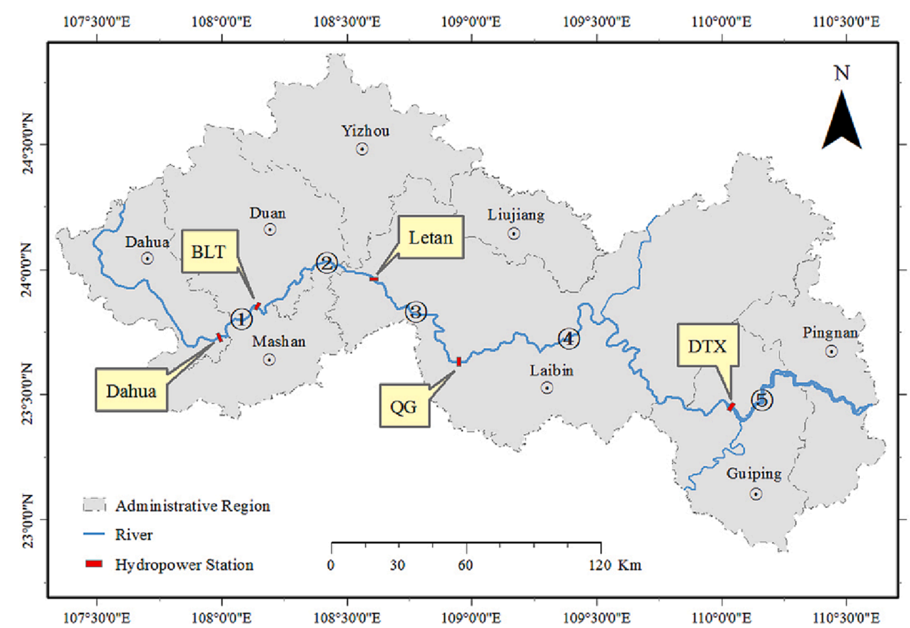


Fig. 11. Geographical location of the selected cascade reservoirs in the Hongshui River basin.

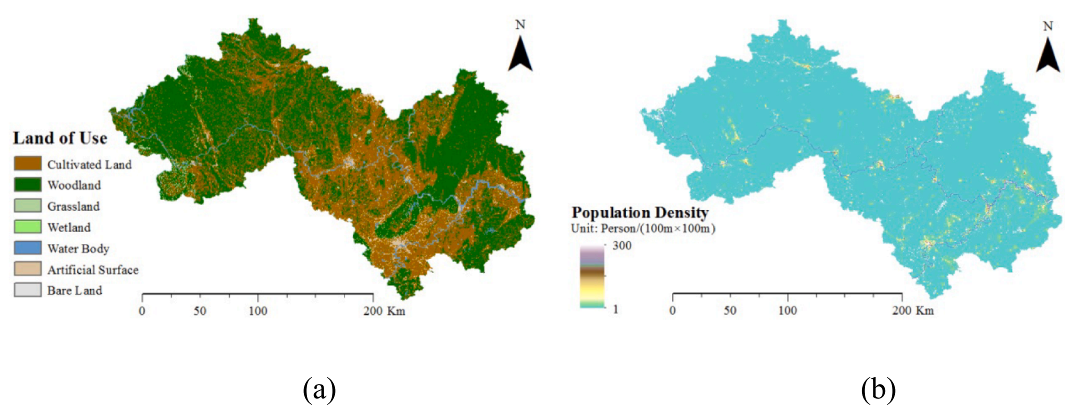


Fig. 12. Overview of the study area. (a) Land use data; (b) Population density distribution.

benefits are quantified regarding the project parameters, which is the same as for individual reservoirs. The indexes of risk consequences are quantified using Eq. (3), which reflects the risk transmission and superposition in cascade reservoirs. For multipurpose projects in China, the highest rank is considered if the results determined by different types of indexes are different (Ren et al., 2017; Wang et al., 2023a). For projects in other countries, the three basic indexes should be assigned different weights depending on the national conditions or policy requirements. After classifying the project rank of the cascade reservoir, the grades of its permanent structures are also determined, as shown in Table 5.

3. Results

3.1. Project overview

Five connected cascade reservoirs, Dahua, BLT, Letan, QG, and DTX, in the Hongshui River basin of China were selected as study objects for rank classification. The basic overview of the projects is shown in Fig. 10 and Table 6 (Zhang et al., 2015; Zhang et al., 2008). The water levels in front of the dam during the operation period of the five reservoirs followed a normal distribution of (155, 2), (128, 1), (112, 0.8), (83, 0.8), and (53, 1.8), respectively (Tang et al., 2021). Considering the cascade reservoir dams as the boundaries, the study area is divided into five

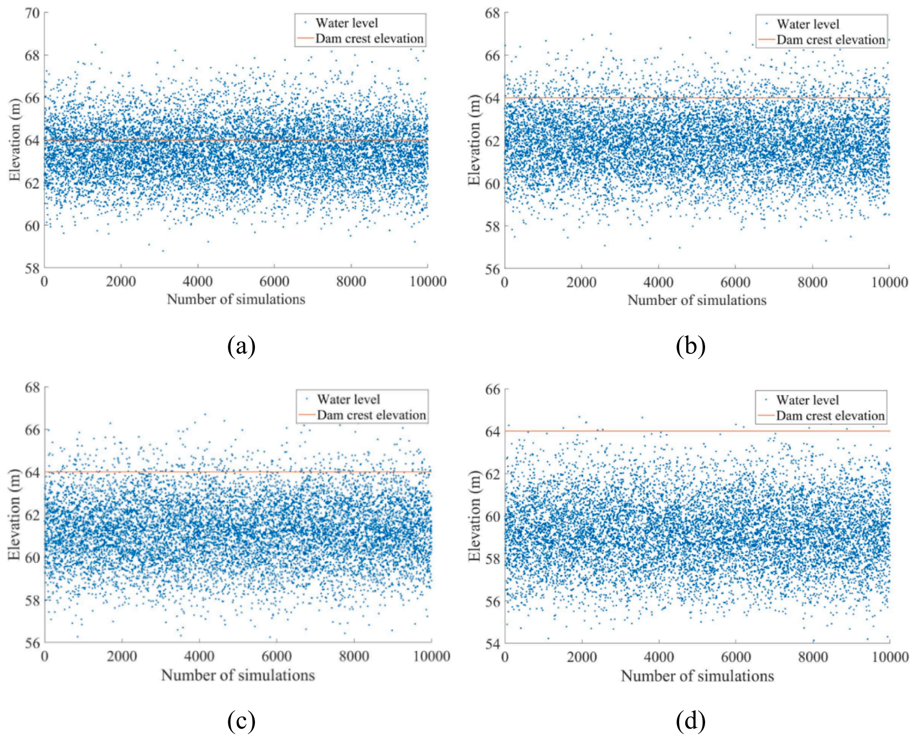


Fig. 13. Water level distribution of DTX Reservoir under different scenarios. (a) Successive dam failures of "Dahua-BLT-Letan-QG;" (b) Successive dam failures of "BLT-Letan-QG"; (c) Successive dam failures of "Letan-QG;" (d) Dam failure of QG reservoir.

segments for targeted analysis, as shown in Fig. 11.

The land use type in the study area is used to set the roughness of flood routing simulation, and the population density distribution is used to calculate the inundated population (Ge et al., 2022; Li et al., 2021), as shown in Fig. 12.

3.2. Analysis and simulation of successive dam failures

The scale and benefit indexes of each cascade reservoir were determined directly from the engineering parameters in Table 6, whereas the risk indexes were quantified through dam failure simulation and flood routing analysis. The capacity parameters indicated that the dam failure of the Dahua Reservoir will cause successive dam failures of the BLT, Letan, and QG reservoirs. Moreover, the dam failure of the BLT and Letan reservoirs will lead to the failures of their adjacent cascades downstream. Therefore, the corresponding CPs of successive dam failures under these scenarios were directly set as 1.

Owing to its large storage capacity, we were uncertain whether the DTX reservoir would break under an upstream dam-break flood. According to Fig. 10, 10,000 groups of water level combinations under different dam failure scenarios are sampled in MATLAB for simulation (Wang et al., 2022; Wang et al., 2023b). The water level distributions in front of the DTX dam under different dam failure scenarios are shown in Fig. 13, and the corresponding conditional probabilities are presented in Table 7.

3.3. Inundation loss statistics and risk consequences calculation

Two software programs, Hec-RAS and ArcGIS, were used for the inundation simulation and visualization of dam failures (Ge et al., 2022; Zelenakova et al., 2019). The inundation area under two dam failure scenarios is shown in Fig. 14. Given that the *LOE* of dam failure is related to the distribution of infrastructure such as factories, enterprises, and transportation arteries downstream (Ge et al., 2020c) and cannot easily be quantified precisely, only the *PAR* was employed in this study as an example of risk consequences. By definition, the product of the inundation area and corresponding population density was set as the value of *PAR*.

In Section 2.5, the segmented losses of each cascade reservoir dam failure were classified as a *DC* and *PC* of the total risk consequences. Considering the Dahua reservoir, its dam failure initially caused a direct inundation of 13,197 persons in segment ①, which was a *DC*. Then, it caused the successive failures of the other four downstream reservoirs. The corresponding inundation in segments ②, ③, ④, and ⑤ were 4464, 24825, 113036, and 523,261 persons, respectively. Combined with the CP of each successive dam failure scenario, its *PC* was 324,734 persons: $(1 \times 4464 + 1 \times 1 \times 24825 + 1 \times 1 \times 1 \times 113036 + 1 \times 1 \times 1 \times 0.3486 \times 37884)$. Using Eq. (3), the *PAR* of each cascade reservoir is calculated, as shown in Table 8 and Fig. 15.

3.4. Rank classification of cascade reservoirs.

As presented in Table 4, the mortality rate f must be specified for practical applications. Based on the dam failure statistics in China, Zhou et al. (2007) proposed a table for the prediction of the f of the *PAR* under different flood severity levels, warning times, and the risk awareness of the public. This table was adopted in this study. Using the results of the water depth, flow velocity, and evolution time of the dam-break flood simulated in the above-mentioned scenarios, f was determined to be 0.001. Subsequently, the critical values of the *PAR* for different project ranks of the cascade reservoirs presented in Table 4 are determined as 87000, 30000, 10000, and 3000 persons.

Regarding the engineering parameters and the calculation results of the *PAR*, the cascade reservoirs were classified according to scale, benefits, and risk consequences. Finally, their project ranks and the grades of the primary structures are determined according to the highest level, as shown in Fig. 16.

Table 7
Calculation of the conditional probabilities (CPs) under different dam failure scenarios of the selected cascade reservoirs in the Hongshui River basin.

Cascade reservoir	Possible scenario of dam failure	The next adjacent cascade	Number of simulations	Number of overtopping of the next adjacent cascade	CP
Dahua	Individual dam failure of Dahua	BLT			1
	Successive dam failures of "Dahua-BLT"	Letan			1
	Successive dam failures of "Dahua-BLT-Letan"	QG			1
	Successive dam failures of "Dahua-BLT-Letan-QG"	DTX	10,000	3486	0.3486
BLT	Individual dam failure of BLT	Letan			1
	Successive dam failures of "BLT-Letan"	QG			1
	Successive dam failures of "BLT-Letan-QG"	DTX	10,000	787	0.0787
Letan	Individual dam failure of Letan	QG			1
	Successive dam failures of "Letan-QG"	DTX	10,000	343	0.0343
QG	Individual dam failure of QG	DTX	10,000	14	0.0014

3.5. Further validation and refinement.

To further demonstrate the generalizability and applicability of the method proposed in this study, cascade reservoirs located in another basin were selected for analysis, focusing on the core processes and results of the application method.

(1) Project Overview and Data Collection

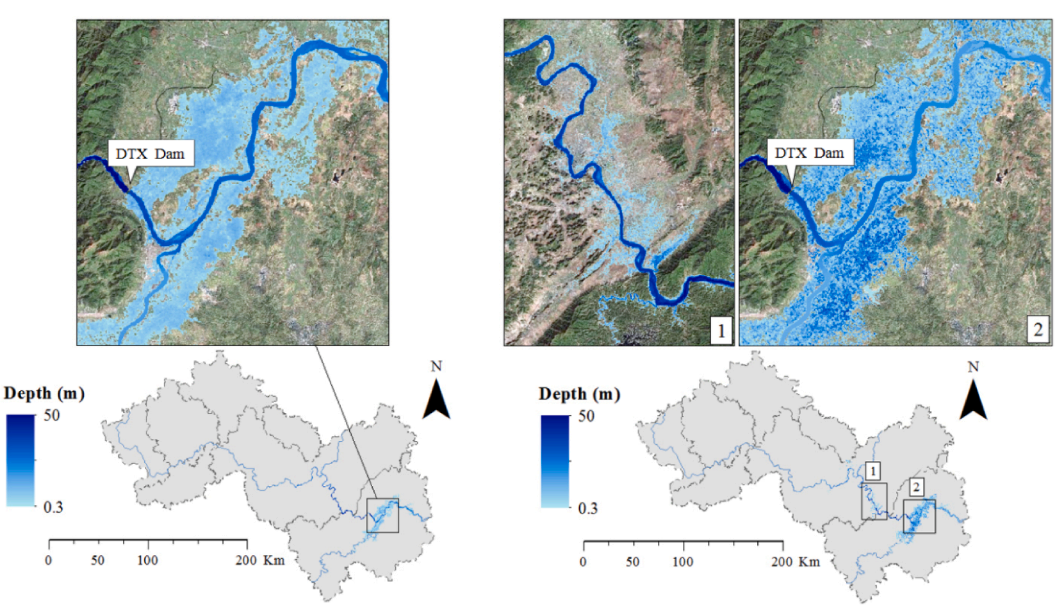
Three cascade reservoirs in the Dadu River basin were selected for further validation. The geographical locations, an overview of the study area, and engineering parameters of these cascade reservoirs are shown in Fig. 17 and Table 9.

(2) CP of successive dam failures

According to Fig. 10, the possible dam failure scenarios were

Table 8
Statistics of inundation population and risk consequences of dam failure of each cascade reservoir.

Cascade reservoir	Inundation population		Risk consequences of dam failure (Taking *PAR* as examples)		
	Segment	Population (persons)	*DC*	*PC*	Sum
Dahua	①	13,197	13,197	324,734	337,931
	②	4464			
	③	24,825			
	④	113,036			
	⑤	523,261			
BLT	②	3933	3933	176,871	180,804
	③	23,662			
	④	112,562			
	⑤	516,475			
Letan	③	22,598	22,598	120,134	142,732
	④	103,172			
	⑤	494,533			
QG	④	75,185	75,185	681	75,866
	⑤	486,756			
DTX	⑤	479,935	479,935		479,935



(a) (b)

Fig. 14. Inundation area under different dam failure scenarios. (a) Dam failure of DTX reservoir; (b) Successive dam failures of "Dahua-BLT-Letan-QG-DTX.".

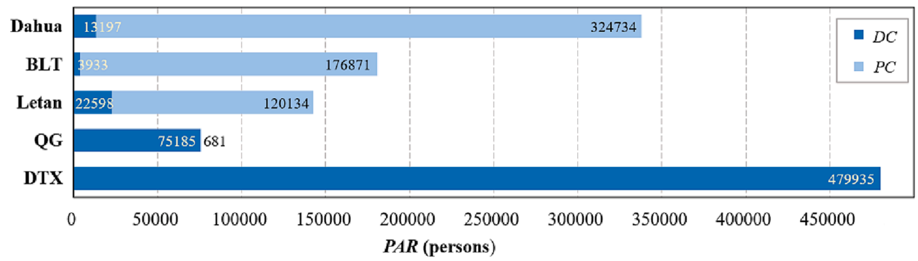


Fig. 15. *PAR* of each cascade reservoir under risk transmission and superimposition.

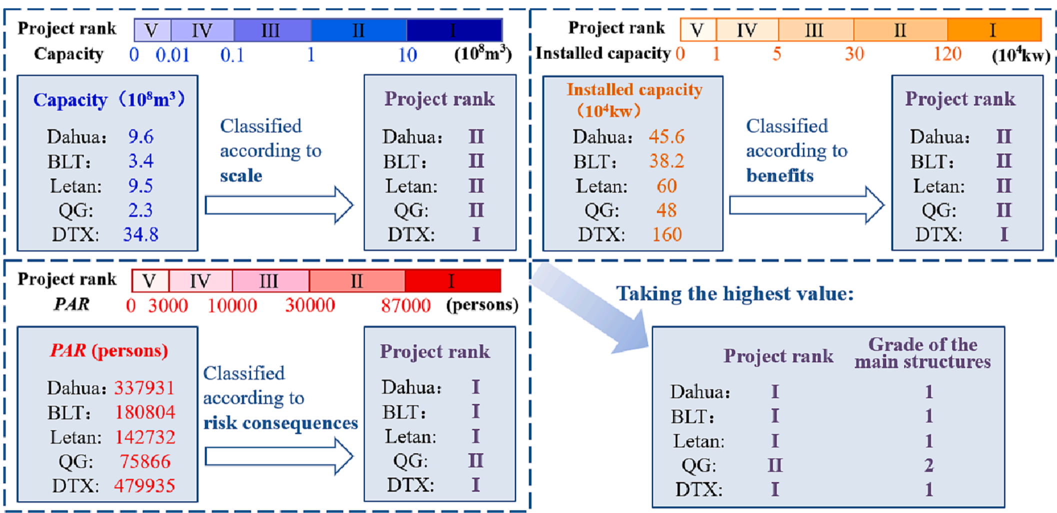


Fig. 16. Rank classification of the selected cascade reservoirs in the Hongshui River basin.

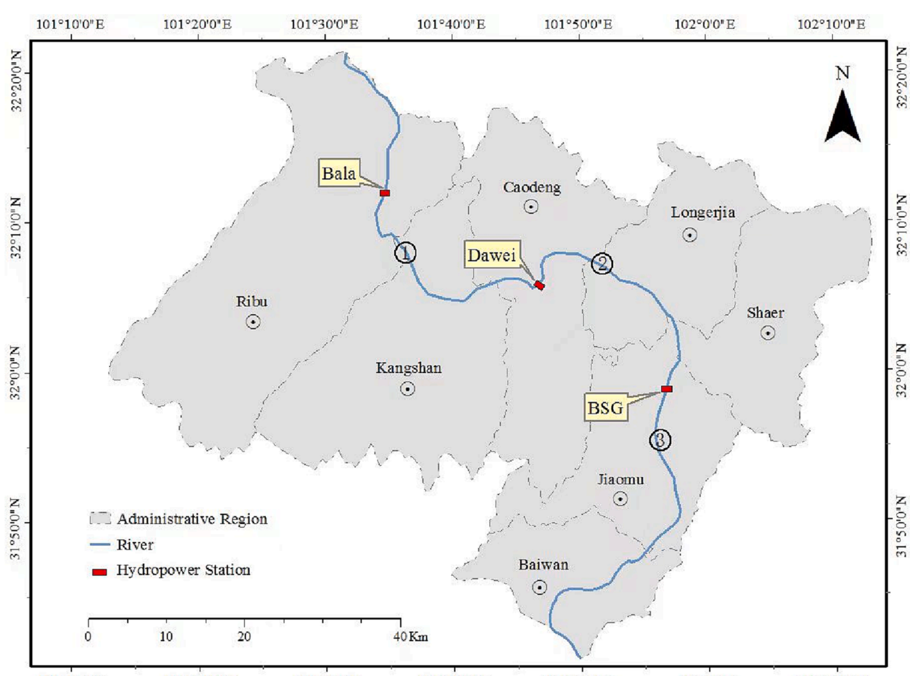


Fig. 17. Geographical location of the selected cascade reservoirs in the Dadu River basin.

analyzed and simulated. The corresponding CPs under different dam failure scenarios are shown in Table 10.

(3) Inundation loss statistics under different dam failure scenarios

Through software simulation, the inundation area under different dam failure scenarios was obtained. Combining the population density distribution and CPs of successive dam failures, the *PAR* of each cascade reservoir is calculated using Eq. (3), as shown in Table 11 and Fig. 18.

Table 9
Parameter data of the selected cascade reservoirs in the Dadu River basin.

Reservoir	Total capacity (10^8 m^3)	Dam crest elevation (m)	Normal pool level (m)	Checking flood level (m)	Protected population (thousand persons)	Installed capacity (10^4kw)
Bala	1.28	2925	2920	2922	41	70
Dawei	1.4	2690	2686	2688	48	27
BSG	2.48	2608	2600	2603	57	36

Table 10
Calculation of the CPs under different dam failure scenarios of the selected cascade reservoirs in the Dadu River basin.

Cascade reservoir	Possible scenario of dam failure	The next adjacent cascade	Number of simulations	Number of overtopping of the next cascade	CP
Bala	Individual dam failure of Bala	Dawei	10,000	10,000	1
	Successive dam failures of “Bala-Dawei”	BSG	10,000	10,000	1
Dawei	Individual dam failure of Dawei	BSG	10,000	8863	0.8863

Table 11
Statistics of inundation population and risk consequences of the selected cascade reservoirs in the Dadu River basin.

Cascade reservoir	Inundation population		Risk consequences of dam failure (Taking *PAR* as examples)		
	Segment	Population (persons)	*DC*	*PC*	Sum
Bala	①	7568	7568	25,705	33,273
	②	8172			
	③	17,533			
Dawei	②	7785	7785	14,674	22,459
	③	16,556			
BSG	③	15,935	15,935		15,935

Owing to the lack of social risk criteria and data from other countries, the selected case experiment is a group of cascade reservoirs located in China. Therefore, the standard in Table 3 can be used directly. For cascade reservoirs in other countries, additional steps are needed. For example, the threshold values of the *LOL* should be derived by applying the method in Section 2.4 in combination with the social risk criteria of that country. Thus, the standard in Table 3 will be updated appropriately. Nevertheless, the primary methodology and process are still generalizable.

According to the simulation results of the dam-break flood and the recommended table for the prediction of the mortality rate, f was determined as 0.003 in all the cases. Subsequently, the critical values of the *PAR* for different project ranks of the cascade reservoirs presented in Table 4 are set as 29000, 10000, 3333, and 1000 persons. Finally, the cascade reservoirs are classified, as shown in Fig. 19.

4. Discussion

(a) Fig. 16 shows that if risk consequences are not considered, only the DTX reservoir will be a Class I project according to the scale and benefits, whereas the other four reservoirs will be Class II projects. Table 6 and Fig. 13 show that if risk transmission and superposition are not considered and only the *DC* is calculated as risk consequences, the direct *PAR* of the DTX reservoir will exceed 87,000 and its project rank will be Class I. The direct *PAR*s of QG, Letan, BLT, and Dahua reservoirs will be in the range of 30000–87000, 10000–30000, 0–3000, and 10000–30000, and their project ranks will be Classes II, III, V, and IV according to the risk consequences, respectively. In contrast, the project ranks and primary structure grades of the four upstream cascade reservoirs increased after adopting the rank classification method proposed in this study.

(b) For projects with severe accident consequences, the current standard for rank classification of water and hydropower projects in China particularly stipulates that the grades of their primary structures should be raised by one level. Similarly, several existing studies (Zhou et al., 2015; Zhou et al., 2020) proposed that the project rank of a cascade reservoir that will cause dam failures downstream under effective early warning should be raised from the original one. These procedures are consistent with the aforementioned results of rank classification. Moreover, this study weighted the segmented losses caused by dam-break floods following the CPs of successive dam failures. Therefore, risk transmission and superposition effects were reflected, thus improving the rationality of the risk consequence assessment of cascade reservoirs.

(c) In the current standards of China and other countries, the “Protected population” is considered one of the indexes of flood control benefits, representing the permanent population in downstream protected areas (Ge et al., 2022). However, it differs from the population that will be inundated by a dam-break flood and therefore cannot be used to quantify risk consequences. In contrast, the *PAR* directly represents the population exposed to the inundation area and can be determined through flood simulation. Most importantly, the thresholds of the *PAR* allowed for

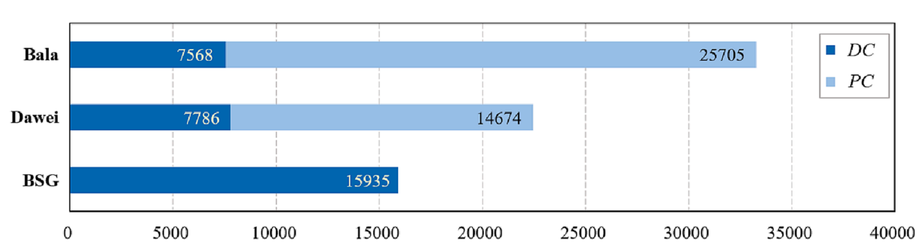


Fig. 18. *PAR* of the selected cascade reservoirs in the Dadu River basin.(4) Rank classification of cascade reservoirs.

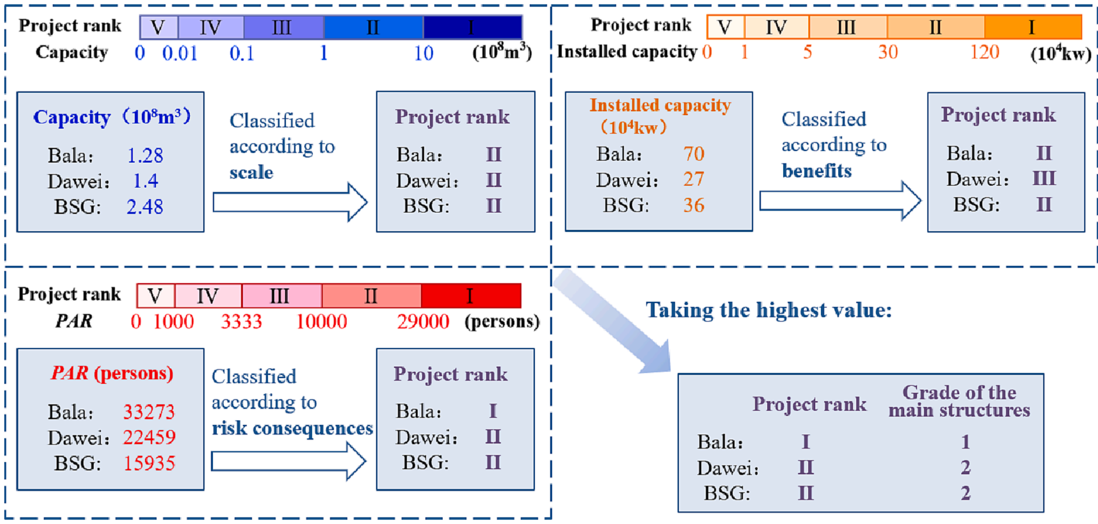


Fig. 19. Rank classification of the selected cascade reservoirs in the Dadu River basin.

different project ranks can be determined by referencing the social risk criteria and the f of dam failure. Therefore, the *PAR* can be effectively used as an index of risk consequences in the rank classification of reservoir projects.

(d) As f is closely related to flood severity, warning time, and the risk awareness of the public, its value is not specifically constrained in the rank classification standard proposed in this study. However, it is analyzed and quantified in engineering applications. Thus, the determination of the project rank is closely related to f, providing an incentive for reservoir management to identify and address risk. To avoid being classified as a high-rank project that requires high maintenance costs and limits the failure probability, f and *LOE* should be reduced by improving the emergency response plan and infrastructure layout (Ge et al., 2020c; Ge et al., 2022). Then, the project rank will be constrained to reduce its risk consequences. This method is consistent with the concept of dam risk management through a combination of engineering and non-engineering measures (Li et al., 2015a).

(e) Although hydropower projects are built primarily to supply sustainable energy and generate socioeconomic benefits, the risk they pose to the downstream cannot be ignored (Pisaniello et al., 2012). Internationally, dam failure consequences are used as important bases for classifying reservoir projects and are thus scientific and effective procedures from the perspective of risk management. Currently, the universal applicability of classifying reservoirs in China based on dam failure consequences has yet to be further demonstrated, owing to the existing differences in the socio-economic development levels within developed countries. However, this remains a potential area for future research (Ren et al., 2017). Considering the severe consequences of successive dam failures, the risk concept should be applied to the rank classification of cascade reservoirs as a priority and gradually extended to general reservoirs.

5. Conclusions

Cascade reservoirs have long spatial spans and present considerable management challenges as they run through the entire basin. To propose scientific and practical methods for the rank classification of cascade reservoirs, we conducted a series of studies and achieved the following results: (1) An index system for the rank classification of cascade reservoirs based on scale, benefit, and risk was constructed; (2) The critical values for the *LOL* allowed for different project ranks were formulated, and the thresholds of the *PAR* were further derived through the f of dam failure; (3) Risk transmission and superposition effects were quantified, and the calculation formula of the risk consequences of cascade reservoirs was proposed; (4) After applying the proposed method to five cascade reservoirs, the rank classification results were higher than those obtained using the current standard, thus validating the feasibility of the proposed method.

Although cascade reservoirs in China were selected for specific analysis in the determination of index thresholds, the analytical model proposed in this study is also applicable to cascade reservoirs in other countries, especially the method of quantifying risk consequence indexes and the idea of determining the allowed thresholds through social risk criteria. In addition, the reasonable quantification of the f of the *PAR* is crucial for the determination of the project rank. This is briefly analyzed in this study based on existing results. In future studies, we will improve the practicality of the quantification method and the accuracy of the calculation results.

CRediT authorship contribution statement

Te Wang: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Zongkun Li:** Conceptualization, Formal analysis, Supervision, Funding acquisition. **Wei Ge:** Methodology, Validation, Writing – review & editing, Funding acquisition. **Yadong Zhang:** Formal analysis. **Yutie Jiao:** Validation. **Laihong Jing:** Investigation. **Pieter van Gelder:** Investigation.

Declaration of Competing 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.

Data availability

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

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References

Bai, T., Wei, J., Chang, O., Yang, W., Huang, Q., 2019. Optimize multi-objective transformation rules of water-sediment regulation for cascade reservoirs in the Upper Yellow River of China, 123987 J. Hydrol. 577. https://doi.org/10.1016/j.jhydrol.2019.123987.

Dewals, B., Erpicum, S., Detrembleur, S., Archambeau, P., Pirotton, M., 2011. Failure of dams arranged in series or in complex. Nat. Hazards 56 (3), 917–939. https://doi.org/10.1007/s11069-010-9600-z.

Escuder-Bueno, I., Mazza, G., Morales-Torres, A., Castillo-Rodriguez, J.T., 2016. Computational aspects of dam risk analysis: findings and challenges. Engineering. 2 (3), 319–324. https://doi.org/10.1016/J.Eng.2016.03.005.

Faucheux, N.M., Sample, A.R., Aldridge, C.A., Norris, D.M., Owens, C., Starnes, V.R., VanderBloemen, S., Miranda, L.E., 2022. Reservoir attributes display cascading spatial patterns along river basins. Water Resour. Res. 58 (1) https://doi.org/10.1029/2021WR029910.

Ge, W., Li, Z., Liang, R., Li, W., Cai, Y., 2017. Methodology for establishing risk criteria for dams in developing countries, case study of China. Water Resour. Manag. 31 (13), 4063–4074. https://doi.org/10.1007/s11269-017-1728-0.

Ge, W., Li, Z., Li, W., Wu, M., Li, J., Pan, Y., 2020a. Risk evaluation of dam-break environmental impacts based on the set pair analysis and cloud model. Nat. Hazards 104, 1641–1653. https://doi.org/10.1007/s11069-020-04237-9.

Ge, W., Qin, Y., Li, Z., Zhang, H., Gao, W., Guo, X., Song, Z., Li, W., van Gelder, P., 2020b. An innovative methodology for establishing societal life risk criteria for dams: a case study to reservoir dam failure events in China, 101663 Int. J. Disast. Risk Re. 49. https://doi.org/10.1016/j.ijdrr.2020.101663.

Ge, W., Sun, H., Zhang, H., Li, Z., Guo, X., Wang, X., Qin, Y., Gao, W., van Gelder, P., 2020c. Economic risk criteria for dams considering the relative level of economy and industrial economic contribution, 138139 Sci. Total Environ. 725. https://doi.org/10.1016/j.scitotenv.2020.138139.

Ge, W., Wang, X., Li, Z., Zhang, H., Guo, X., Wang, T., Gao, W., Lin, C., van Gelder, P., 2021. Interval analysis of the loss of life caused by dam failure. J. Water Res. Plan Man. 147 (1), 04020098. https://doi.org/10.1061/(Asce)Wr.1943-5452.0001311.

Ge, W., Jiao, Y., Wu, M., Li, Z., Wang, T.e., Li, W., Zhang, Y., Gao, W., van Gelder, P., 2022. Estimating loss of life caused by dam breaches based on the simulation of floods routing and evacuation potential of population at risk. J. Hydrol. 612, 128059.

Ghimire, S.N., Schulenberg, J.W., 2022. Impacts of climate change on the environment, increase in reservoir levels, and safety threats to earthen dams: post failure case study of two cascading dams in Michigan. Civ. Environ. Eng. 18 (2), 551–564. https://doi.org/10.2478/cee-2022-0053.

Hariri-Ardebili, M., 2018. Risk, Reliability, Resilience (R-3) and beyond in dam engineering: a state-of-the-art review. Int. J. Disast. Risk Re. 31, 806–831. https://doi.org/10.1016/j.ijdrr.2018.07.024.

Jonkman, S.N., Lentz, A., Vrijling, J.K., 2010. A general approach for the estimation of loss of life due to natural and technological disasters. Reliab. Eng. Syst. Safe. 95 (11), 1123–1133. https://doi.org/10.1016/j.ress.2010.06.019.

Latrubesse, E.M., Arima, E.Y., Dunne, T., Park, E., Baker, V.R., d'Horta, F.M., Wight, C., Wittmann, F., Zuanon, J., Baker, P.A., Ribas, C.C., Norgaard, R.B., Filizola, N., Ansar, A., Flyvbjerg, B., Stevaux, J.C., 2017. Damming the rivers of the Amazon basin. Nature 546 (7658), 363–369. https://doi.org/10.1038/nature22333.

Li, Z., Ge, W., Wang, J., Li, W., 2015b. Risk criteria and application on reservoir dams in China. J. Hydraul. Eng. (China) 46 (5), 567. https://doi.org/10.13243/jcnki.slxb.20141359.

Li, Z., Li, W., Ge, W., 2018. Weight analysis of influencing factors of dam break risk consequences. Nat. Hazard Earth Sys. 18 (12), 3355–3362. https://doi.org/10.5194/nhess-18-3355-2018.

Li, W., Li, Z., Ge, W., Wu, S., 2019a. Risk evaluation model of life loss caused by dam-break flood and its application. Water 11 (7). https://doi.org/10.3390/w11071359.

Li, Z., Wang, T., Ge, W., Wei, D., Li, H., 2019b. Risk analysis of earth-rock dam breach based on dynamic Bayesian network. Water 11 (11), 2305. https://doi.org/10.3390/w11112305.

Li, Z., Zhang, Y., Wang, J., Ge, W., Li, W., Song, H., Guo, X., Wang, T., Jiao, Y., 2021. Impact evaluation of geomorphic changes caused by extreme floods on inundation area considering geomorphic variations and land use types. Sci. Total Environ. 754, 142424. https://doi.org/10.1016/j.scitotenv.2020.142424.

Li, S., Zhou, X., Wang, Y., Zhou, J., Du, X., Chen, Z., 2015a. Study of risk acceptance criteria for dams. Sci. China Technol. Sc. 58 (7), 1263–1271. https://doi.org/10.1007/s11431-015-5864-6.

Lima, D., Lima, G., Molina, V., Fais, L., 2022. Application of a simplified methodology for classification of small dams in cascade. Revista Ambiente Água 17 (1), e2790–e. https://doi.org/10.4136/ambi-agua.2790.

Lin, P., Huang, B., Li, Q.B., Wang, R.K., 2015. Hazard and seismic reinforcement analysis for typical large dams following the Wenchuan earthquake. Eng. Geol. 194, 86–97. https://doi.org/10.1016/j.enggeo.2014.05.011.

Lu, S., Shang, Y., Li, W., Peng, Y., Wu, X., 2018. Economic benefit analysis of joint operation of cascaded reservoirs. J. Clean Prod. 179, 731–737. https://doi.org/10.1016/j.jclepro.2017.08.140.

Manikkuwahandi, T.D., Hornberger, G.M., 2021. Deriving Reservoir Cascade Operation Rules for Variable Streamflows by Optimizing Hydropower Generation and Irrigation Water Delivery. J. Water. Resour. Plan. Manag. 147 (7) https://doi.org/10.1061/(ASCE)WR.1943-5452.0001372.

McGuire, M., VandenBerge, D., 2017. Interpretation of shear strength uncertainty and reliability analyses of slopes. Landslides 14 (6), 2059–2072. https://doi.org/10.1007/s10346-017-0836-5.

Mehta, A., Weeks, C., Tyquin, E., 2020. Towards preparedness for dam failure: an evidence base for risk communication for downstream communities, 101820 Int. J. Disast. Risk Res. 50. https://doi.org/10.1016/j.ijdrr.2020.101820.

Micovic, Z., Hartford, D.N., Schaefer, M.G., Barker, B.L., 2016. A non-traditional approach to the analysis of flood hazard for dams. Stoch. Environ. Res. Risk Assess. 30 (2), 559–581. https://doi.org/10.1007/s00477-015-1052-2.

Peng, M., Zhang, L., 2013. Dynamic decision making for dam-break emergency management - Part 1: theoretical framework. Nat. Hazard Earth Sys. 13 (2), 425–437. https://doi.org/10.5194/nhess-13-425-2013.

Pereira, R., Batista, A.L., Neves, L.C., 2018. Probabilistic model for the representation of the reservoir water level of concrete dams during normal operation periods. Water Resour. Manag. 32 (9), 3041–3052. https://doi.org/10.1007/s11269-018-1973-x.

Pisaniello, J.D., Tingey-Holyoak, J., Burritt, R.L., 2012. Appropriate small dam management for minimizing catchment-wide safety threats: international benchmarked guidelines and demonstrative cases studies. Water Resour. Res. 48 https://doi.org/10.1029/2011wr011155.

Rashid, M.U., Latif, A., Azmat, M., 2018. Optimizing irrigation deficit of multipurpose cascade reservoirs. Water Resour. Manag. 32 (5), 1675–1687. https://doi.org/10.1007/s11269-017-1897-x.

Ren, M.L., He, X.Y., Kan, G.Y., Wang, F., Zhang, H.B., Li, H., Cao, D.L., Wang, H., Sun, D. Y., Jiang, X.M., Wang, G., Zhang, Z.B., 2017. A Comparison of flood control standards for reservoir engineering for different countries. Water 9 (3). https://doi.org/10.3390/w9030152.

Shao, C., Gu, C., Meng, Z., Hu, Y., 2020. Integrating the finite element method with a data-driven approach for dam displacement prediction. Adv. Civ. Eng. 2020, 1–16.

Sharifi, M.R., Akbarifard, S., Qaderi, K., Madadi, M.R., 2021. Developing MSA algorithm by new fitness-distance-balance selection method to optimize cascade hydropower reservoirs operation. Water Resour. Manag. 35 (1), 385–406. https://doi.org/10.1007/s11269-020-02745-8.

Sheng, J., Fu, Z., 2010. A comparative study of dam classification between the Chinese method and the international practices. Hydro-Sci. Eng. (China) 31 (2), 7–13. https://doi.org/10.16198/j.cnki.1009-640x.2010.02.009.

Tang, Y., Chen, L., She, Z., 2021. Evaluation of instream ecological flow with consideration of ecological responses to hydrological variations in the downstream Hongshui River Basin, China. Ecol. Indic. 130, 108104.

The Ministry of Water Resources of the People's Republic of China, 2017. SL 252-2017, Standard for Rank Classification and Flood Protection Criteria of Water and Hydropower Projects. China Water & Power Press, Beijing.

Wang, T.e., Li, Z., Ge, W., Zhang, Y., Jiao, Y., Sun, H., Zhang, H., 2022. Calculation of dam risk probability of cascade reservoirs considering risk transmission and superposition. J. Hydrol. 609, 127768.

Wang, T.e., Li, Z., Ge, W., Zhang, Y., Jiao, Y., Zhang, H., Sun, H., van Gelder, P., 2023a. Risk assessment methods of cascade reservoir dams: a review and reflection. Nat. Hazards 115 (2), 1601–1622.

Wang, T.e., Li, Z., Ge, W., Zhang, H., Zhang, Y., Sun, H., Jiao, Y., 2023b. Risk consequence assessment of dam breach in cascade reservoirs considering risk transmission and superposition. Energy 265, 126315.

Wang, C., Ren, Q., Zhou, J., Yang, Y., 2020. Statistical data-based approach to establish risk criteria for cascade reservoir systems in China. Environ. Earth Sci. 79 (10) https://doi.org/10.1007/s12665-020-08951-2.

Wilde, M., Johansson, F., 2013. System reliability of concrete dams with respect to foundation stability: application to a spillway. J. Geotech. Geoenviron. 139 (2), 308–319. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000761.

Wu, M., Wu, Z., Ge, W., Wang, H., Shen, Y., Jiang, M., 2021. Identification of sensitivity indicators of urban rainstorm flood disasters: a case study in China, 126393 J. Hydrol. 2021 (599). https://doi.org/10.1016/j.jhydrol.2021.126393.

Zelenakova, M., Fijko, R., Labant, S., Weiss, E., Markovic, G., Weiss, R., 2019. Flood risk modelling of the Slatvinec stream in Kruzlov village, Slovakia. J. Clean. Prod. 212, 109–118. https://doi.org/10.1016/j.jclepro.2018.12.008.

Zhang, K., Fang, S., Wang, S., Zhang, Y., Zhang, W., Gu, J.W., Chen, X.L., Liu, E.H., 2015. Effect of cascade reservoirs on flood routing in the Hongshui River, Southern China. Matec. Web Conf. 25, 01012.

Zhang, W., Li, J., Liu, P., Lei, X., Chen, J., Yeh, W.W.G., 2021. When to start an adaptation strategy in response to climate change in reservoir system management. J. Hydrol. 603, 127111.

Zhang, S., Lu, X., Higgitt, D., Chen, C., Han, J., Sun, H., 2008. Recent changes of water discharge and sediment load in the Zhujiang (Pearl River) Basin, China. Glob. Planet. Change. 60 (3–4), 365–380. https://doi.org/10.1016/j.gloplacha.2007.04.003.

Zhou, X., Chen, Z., Zhou, J., Guo, X., Du, X., Zhang, Q., 2020. A quantitative risk analysis model for cascade reservoirs overtopping: principle and application. Nat. Hazards 104 (1), 249–277. https://doi.org/10.1007/s11069-020-04167-6.

Zhou, Y., Guo, S., Liu, P., Xu, C., 2014. Joint operation and dynamic control of flood limiting water levels for mixed cascade reservoir systems. J. Hydrol. 519, 248–257. https://doi.org/10.1016/j.jhydrol.2014.07.029.

Zhou, Y., Guo, S., Chang, F., Liu, P., Chen, A., 2018. Methodology that improves water utilization and hydropower generation without increasing flood risk in mega cascade reservoirs. Energy 143, 785–796. https://doi.org/10.1016/j.energy.2017.11.035.

Zhou, K., Li, L., Sheng, J., 2007. Evaluation model of loss of life due to dam breach in China. J. Safety Environ. (China) 7 (3), 145–149. https://doi.org/10.3969/j.issn.1009-6094.2007.03.037.

Zhou, J., Wang, H., Chen, Z., Zhou, X., Li, B., 2015. Evaluations on the safety design standards for dams with extra height or cascade impacts. Part I: fundamentals and criteria. J. Hydraul. Eng. (China) 46 (5), 505–514. https://doi.org/10.13243/j.cnki.slxb.20150249.

Zhu, Y., Tang, H., 2023. Automatic damage detection and diagnosis for hydraulic structures using drones and artificial intelligence techniques. Remote Sens. 15 (3), 615. https://doi.org/10.3390/rs15030615.

Zhu, Y., Niu, X., Gu, C., Yang, D., Sun, Q., Rodriguez, E., 2020. Using the DEMATEL-VIKOR method in dam failure path identification. Int. J. Environ. Res. Public Health 17 (5), 1480. https://doi.org/10.3390/ijerph17051480.

Zhu, Y., Niu, X., Gu, C., Dai, B.o., Huang, L., Kumarappan, N., 2021. A fuzzy clustering logic life loss risk evaluation model for dam-break floods. Complexity 2021, 1–14.