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**DOI**
10.1016/j.energy.2022.126315

**Publication date**
2023

**Document Version**
Final published version

**Published in**
Energy

Energy 265 (2023) 126315

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

# Risk consequence assessment of dam breach in cascade reservoirs considering risk transmission and superposition

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ARTICLE INFO

*Keywords:*
Cascade reservoirs
Dam breach
Risk transmission
Risk management
Loss

ABSTRACT

Compared with a single reservoir, the risk in cascade reservoirs has the transmission and superposition effect, which increases the complexity of its risk consequence assessment. In view of this problem, the direct consequence (*DC*) and potential consequence (*PC*) were defined as two parts of the dam breach risk consequence of cascade reservoirs. The upstream dam-break flood inundation line and the downstream reservoir land acquisition line were taken as the upper and lower boundaries of the assessment space, which made the risk consequence assessment more intuitive and further improved its scientificity and practicability. Subsequently, the conditional probability of downstream dam breach under the upstream dam-break flood was determined to quantify the risk transmission and superposition. On this basis, the relevant concepts and formulas for calculating the dam breach risk consequence in cascade reservoirs were proposed. Taking five cascade reservoirs as examples, the risk consequences of each cascade dam breach were evaluated. The results show that the proposed method is effective in assessing the risk consequence of dam breach in cascade reservoirs and is more in line with the connotation of dam risk management, which can provide reference for the design and risk control of cascade reservoirs.

## 1. Introduction

With the maturity of hydropower development technology and the continuous expansion of energy demand, hydropower construction modes in most countries are gradually moving towards river basin development and cascade reservoirs construction [1–3]. Despite generating enormous benefits, dams may break and cause destructive floods, resulting in giant threats to the downstream residents and the economy [4–6]. Compared with a single reservoir, the 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 [7,8]. In May 2020, heavy precipitation in Michigan led to the breaches of two cascade dams, the Edenville Dam and Sanford Dam, resulting in about $100 million in damages and the evacuation of about 11,000 residents [9]. In July 2021, the "Yongan-Xinfa" cascade reservoirs in the Nenjiang River Basin of China collapsed, causing 16,660 residents to be affected and 217 $km^2$ of farmland to be submerged [10]. Therefore, it is necessary to carry out risk assessment for cascade reservoirs, which is the key to ensure the safety of the whole basin.

At present, the dam management mode is transitioning from safety management to risk management [11–13]. Safety management is mainly aimed at the analysis and evaluation of the structural safety of dams. In contrast, risk management focuses on the risk probability and consequences of dam failures, which is more scientific and comprehensive. Generally, probability and consequence are regarded as two aspects of risk [14,15]. Risk consequence is defined as the possible consequence of an uncertain risk event [15–17]. Different from the actual dam breach loss data obtained from post-disaster statistics, this study mainly focuses on the assessment of the risk consequences, with the aim of providing a reasonable measurement of the possible consequence of the dam breach in cascade reservoirs, so as to guide the engineering design and risk control.

As an uncertain event with low probability but disastrous consequences, dam breach has been concerned by more and more scholars. Numerous research results have been achieved in the dam breach risk

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https://doi.org/10.1016/j.energy.2022.126315
Received 11 August 2022; Received in revised form 21 November 2022; Accepted 30 November 2022
Available online 3 December 2022

consequence assessment, which are roughly classified into empirical models based on historical data [15,17], physical models based on disaster mechanism analysis [18,19], quantitative and semi quantitative evaluation models based on relevant mathematical theories [5,11,20]. In contrast, the current research on the dam breach consequence of cascade reservoirs is obviously insufficient, and the relevant results need to be further demonstrated in engineering practice. Through a shallow water dynamic model, Riha et al. [21] summarized the typical dam-break flood routing characteristics of small cascade dams, which can be used to analyze the inundation of successive dam breach; Larruari and Lall [22] proposed a framework to assess the hazards caused by dam breaches to the downstream residents and critical infrastructures; Hu et al. [8] combined the hydraulic characteristics of cascade reservoirs with flood routing simulation to carry out numerical simulation and risk assessment; Zhou et al. [23] developed a quantitative and practical risk analysis model for analyzing overtopping failure of cascade dams.

Unlike the risk probability mainly depends on engineering factors, the risk consequence of dam breach is the synthesis of the corresponding losses under various possible scenarios [5,11]. However, most of the existing studies analyzed the dam breach consequence of cascade reservoirs by supposing a fixed successive dam breach scenario, without considering its probability and the uncertainty of dam-break flood [8,24]. In addition, relevant studies failed to propose an effectively method to quantify the risk transmission and superposition in cascade reservoirs, resulting in a lack of reasonableness in their assessment results.

In practice, the direct loss caused by a single cascade dam breach may not be large, but it has a certain probability to cause the successive dam breaches in the downstream cascades, resulting in huge losses. In this case, how to reasonably measure its risk consequence has become a practical issue. Actually, the assessment methods of risk consequence for a single reservoir dam breach are also applicable to cascade reservoirs, but the consideration of risk correlation needs to be integrated [10]. Therefore, this study aims to propose a practical method for assessing the risk consequence of dam breach in cascade reservoirs, paying careful attention to the risk transmission and superposition.

## 2. Methods

### 2.1. Analysis and decomposition of dam breach risk consequence in cascade reservoirs

According to the relevant research and the actual application in engineering practice, the risk consequence of a dam breach roughly includes life loss, economic loss, social impact and environmental impact [11,20,25]. Among them, life loss, economic loss and environmental impact are considered as three basic categories of the dam breach risk consequence, and social impact is their joint action. The life loss assessment factors include inundated population, early warning time and severity of floods [11,15]; The economic loss includes direct loss and indirect loss [4]; The factors of social and environmental impact assessment include the impact on cultural landscape, cultural relics and historic sites, river morphology and other indicators [15,20].

After a cascade dam breaks, the upstream dam-break flood flows to the downstream reservoir, resulting in the rise of reservoir water level. It is uncertain and probabilistic for a cascade dam breach to cause the successive dam breach in the downstream cascade reservoirs. If the downstream cascade reservoir successfully retain the dam-break flood without overtopping, it will only produce a certain inundation loss within this cascade. If the downstream cascade fails to resist the dam-break flood, that is, the successive breach occurs, the flood will continue to evolve beyond the downstream cascade, further expanding its consequence [26,27].

According to the impact scope of a cascade dam breach in its downstream area, the risk consequence is decomposed into direct consequence (*DC*) and potential consequence (*PC*). *DC* refers to the loss caused by a cascade dam breach directly in the area above the downstream dam, which is inevitable whether the successive dam breaches occur or not. Besides, a cascade dam breach also has the potential to cause the additional loss in the further downstream area by triggering successive dam breaches, which is uncertain and defined as *PC*. The decomposition of dam breach risk consequence in cascade reservoirs is shown in Fig. 1.

It can be seen in Fig. 1 that the loss of dam breach is segmented: $L_{MN}$ represents the loss caused by the dam-break flood in the segment between dams $M$ and $N$; $L_{NK}$ represents the loss caused by the successive dam-break flood in the segment between dams $N$ and $K$; $L_K$ represents the loss caused by the successive dam-break flood in the downstream area of dam $K$. For dam $M$ at the most upstream, $L_{MN}$ is its *DC*. In addition, the breach of dam $M$ may also lead to the successive dam breaches of “*M-N*″ and “*M-N-K*". $PC_{NK}$ and $PC_K$ are the *PC*, which can be quantified through $L_{NK}$ and $L_K$, respectively. Although the *PC* is caused by the successive dam-break flood, it originates from the dam breach of dam $M$. Thus, it is superimposed with *DC* as the risk consequence of dam $M$.

### 2.2. Delimitation of assessment space of dam breach risk consequence in cascade reservoirs

In a cascade reservoir group, the upstream cascade reservoir dam is connected with the backwater surface line of the downstream reservoir through the river channel [28–30]. The inundation loss below the highest inundation line of the upstream dam-break flood is not entirely attributable to the dam breach risk consequence, because the storage of the downstream reservoir has caused a original inundation in this area. Accordingly, the assessment space of dam breach risk consequence in cascade reservoirs should be reasonably defined.

In the actual planning and design of a reservoir project, the land acquisition and resettlement work are usually carried out according to the delimited land acquisition line and resettlement line [31,32]. The land acquisition line and resettlement line are taken into account not only the frequent inundation below the normal pool level, but also a certain flood standard. For example, in the construction of some cascade reservoirs in China, the 5-year flood and 20-year flood were respectively used to delimit the land acquisition line and resettlement line [33]. Then, the government and management departments will make a one-time compensation for the land inundation below the land acquisition line, and the residents below the resettlement line will be relocated and resettled. For the objects between the two lines that may be temporarily inundated in case of a large flood, compensation will be made after they are actually damaged [31,32,34].

After the reservoir impoundment, the land acquisition line will normally be submerged. In contrast, the residential line is drawn for the purpose of transferring residents who may suffer from floods, and is mostly higher than the of the reservoir water level. Therefore, the space below the land acquisition line is considered as the original inundation of the reservoir. Based on the above considerations, the highest inundation line of upstream dam-break flood that can be obtained through simulation and the land acquisition line of the downstream reservoir are taken as the delimited boundaries of dam breach risk consequence assessment space in cascade reservoirs. The space below the land acquisition line is regarded as the original inundation of the reservoir. It is considered that the corresponding inundation loss below the land acquisition line has been compensated in the reservoir planning and construction stage, which is no longer attributed to dam breach inundation. The inundation loss in the space between the land acquisition line and the upstream dam breach flood inundation line is regarded as the risk consequence of dam breach, as shown in Fig. 2.

### 2.3. Quantification of risk transmission and superposition

In fact, the result of risk transmission and superposition is the change of dam breach probability of downstream cascades [27,35]. In previous

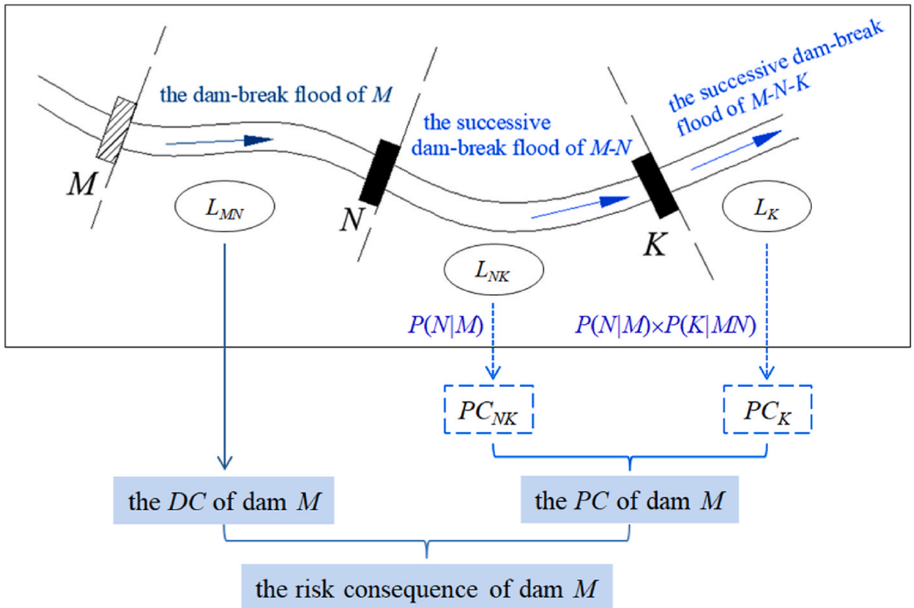



**Fig. 1.** Decomposition of dam breach risk consequence in cascade reservoirs.

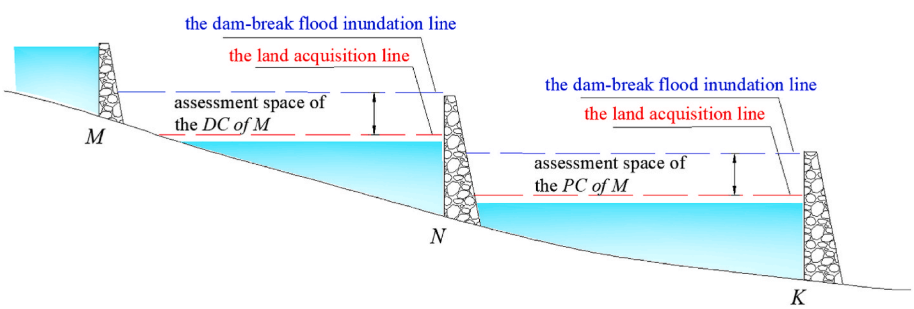



**Fig. 2.** Delimitation of assessment space of dam breach risk consequence in cascade reservoirs.

studies [10], we have decomposed the total risk of a cascade dam into its own risk (*OR*) and additional risk (*AR*): *OR* refers to the breach probability of a cascade dam under its own risk factors without considering the effect of upstream dam-break flood, which is treated to be independent of each other in cascade reservoirs; *AR* refers to the additional breach probability to a cascade dam transmitted from its upstream cascades. On this basis, the risk correlations in cascade reservoirs are manifested through conditional probabilities (CP), as shown in Fig. 3.

As can be seen in Fig. 3, *AR* is the representation of risk transmission and superposition in the dam breach probability of cascade reservoirs, which is effectively quantified by the conditional probabilities. According to the decomposition and definition of dam breach risk consequence in cascade reservoirs, *PC* is actually also a representation of risk transmission and superposition, which can be quantified in terms of the

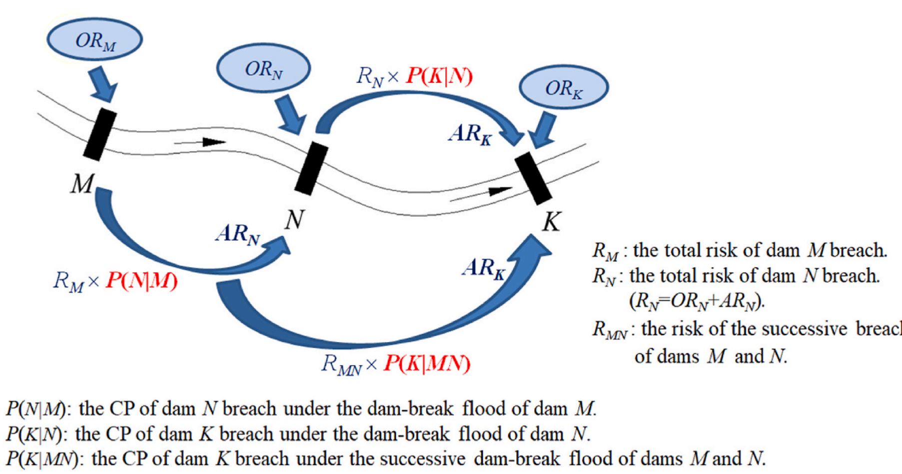



**Fig. 3.** Schematic diagram of risk correlations in cascade reservoirs.

conditional probability of successive breach and the corresponding segmented loss. Therefore, the conditional probability of a cascade dam breach under the upstream dam-break flood is still feasible to quantify the risk transmission and superposition in the risk consequence assessment.

Practice has shown that overtopping is the main breach mode of most dams, especially earth rock dams [36,37]. In view of the huge impact of the upstream dam-break flood on the downstream dam, this study also takes overtopping of the downstream cascade dam as the criterion for the 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. Moreover, the reservoir water level of each cascade reservoir during the operation period is fluctuating, a specific water level can not represent all scenarios [38,39]. 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 uncertain combination of water levels in front of two adjacent cascade dams determine the randomness of their successive breach. Thus, the quantification of the successive breach conditional probability is based on random simulation and mathematical statistics [10]. Through sampling different water level combinations of upstream and downstream cascade reservoirs, the dam-break simulation and flood routing are carried out [10,40]. Ultimately, the frequency of successive breach is calculated and taken as the value of conditional probability (CP), as shown in Fig. 4.

### 2.4. Construction of successive dam breach analysis model

As described, the successive dam breach analysis are not only the key to determine the conditional probability of downstream dam breach under the upstream dam-break flood, but also an important basis for evaluating the dam breach risk consequence. The successive dam breach model of this study is mainly based on dam breach simulation and flood routing [41–43], which includes the following steps: (a) The inflow boundary conditions are set to reflect the inflow process and cause the rise of water level; (b)The dam-break flood is generated and its hydrograph is obtained through dam breach simulation; (c) The downstream area is divided into several grids to calculate the hydraulic characteristics of the dam-break flood and the outflow process; (d) The outflow of upstream dam-break flood becomes the inflow of the downstream reservoir and causes overtopping, then the successive dam-break flood continues to evolve downstream. Therefore, the successive dam breach analysis in cascade reservoirs is realized by simulating several dam breaches in turn, as shown in Fig. 5.

With the development of computer technology, more and more efficient softwares have been used for dam breach simulation and flood routing, such as the MIKE, HEC-RAS, DSS-WISE, and DB-IWHR models [44–46]. In this study, the HEC-RAS software is selected for the simulation and analysis of dam-break flood, which has been widely used because of its easy operation and complete function. Its unsteady flow calculation is mainly based on the Saint Venant equations [47,48]. As shown in Eqs. (1) and (2).

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=0 \tag{1}$$

$$\frac{\partial}{\partial t}\left(\frac{Q}{A}\right)+\frac{\partial}{\partial x}\left(\frac{\beta Q^2}{2A^2}\right)+g\frac{\partial h}{\partial x}+g(Sf-S0)=0 \tag{2}$$

where $A$ is the cross-sectional area of water discharge, $t$ is the time step, $Q$ is the flow, $x$ is the spatial coordinate, $H$ is the water depth, $S_0$ is the river bottom gradient, $S_f$ is the resistance gradient (gradient of head loss along the way), $K$ is the flow modulus.

Saint Venant equations are generally discretized to obtain their approximate solutions by giving initial and boundary conditions. The upstream and downstream boundary conditions usually include water level boundary, flow boundary and water level flow relationship [8,49]. For the successive dam breach simulation of cascade reservoirs, the inflow of each cascade reservoir is the upstream dam-break flood, and the upstream boundary condition is the flow boundary; the downstream is connected with the river, and the boundary condition is the water level boundary.

### 2.5. Calculation of dam breach risk consequence in cascade reservoirs

By classifying the dam breach risk consequence of cascade reservoirs and delimiting its assessment space, the relevant technologies and methods of dam breach inundation loss assessment for ordinary reservoirs can also be applied to cascade reservoirs [11,17,18]. Based on this, it is only necessary to analyze the conditional probabilities of different successive breach scenarios and the segmented inundation under corresponding dam-break flood.

Taking the dam M at the most upstream in Fig. 1 as an example, its own breach will produce *DC* in the segment between dams M and N. In addition, it may also lead to the breaches of the downstream dam N (the successive dam breach of "M-N″) and dam K (the successive dam breach of "M-N-K″), with corresponding *PC*s in corresponding segments. Thus, the method for dam breach risk consequence calculation of dam M is shown in Eq. (3).

$$CM=DC+PC=LMN+PCNK+PCK \tag{3}$$

where $C_M$ is the total risk consequence of dam M, which mainly includes life loss, economic loss and environmental impact. $L_{MN}$ is the loss caused by dam M breach in the segment between M and N. By definition, *PC* refers to the additional loss that needs to be considered because the dam-break flood may lead to a successive dam breach, which is uncertain and probabilistic. Therefore, the $PC_{NK}$ and $PC_K$ can be further decomposed, as shown in Eq. (4).

$$\begin{cases} PCNK=P(N|M)\times LNK \\ PCK=P(N|M)\times P(K|MN)\times LK \end{cases} \tag{4}$$

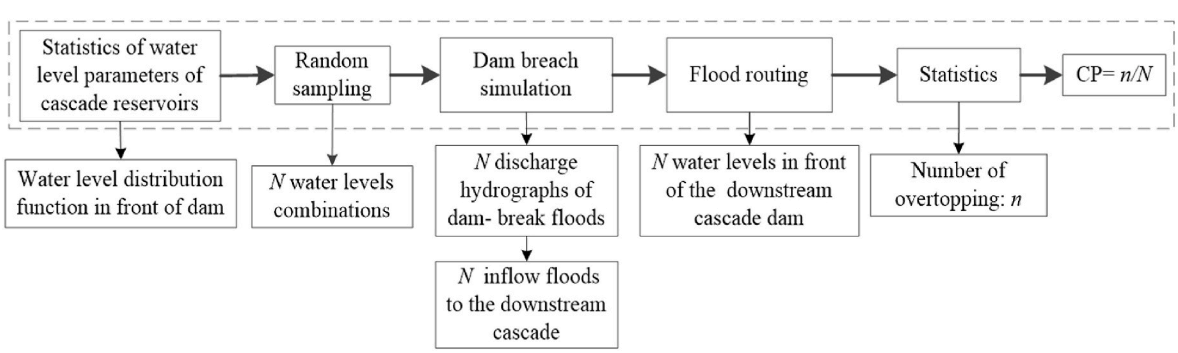



**Fig. 4.** Calculation flow of the conditional probability of successive dam breach.

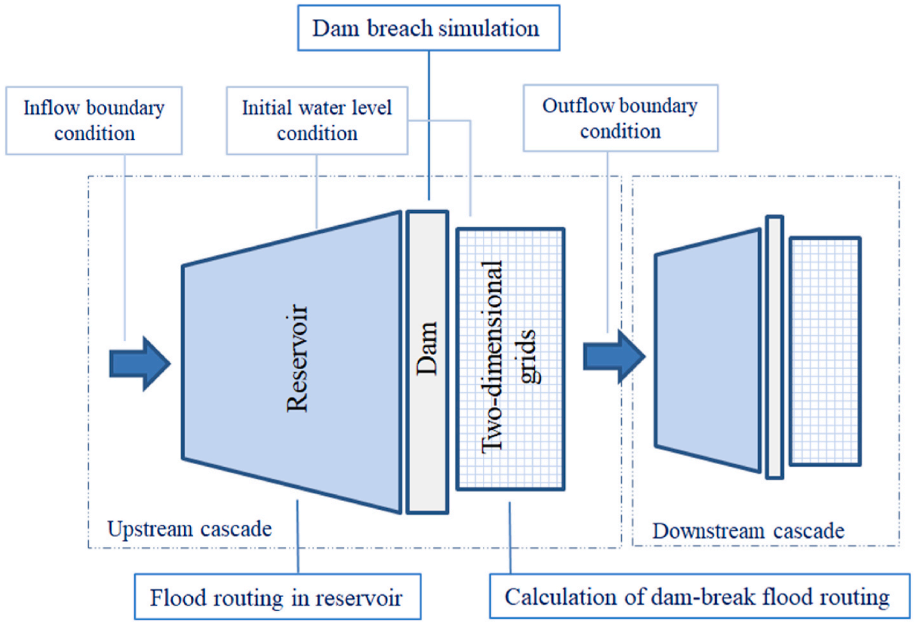



**Fig. 5.** Analysis model of successive dam breach for cascade reservoirs.

where $P(N|M)$ and $P(K|MN)$ are the conditional probabilities, which represent the breach probability of dam N under the dam-break flood of dam M, and the breach probability of dam K under the successive dam-break flood of dams M and N, respectively.

These segmented losses can be calculated according to the assessment methods of flood inundation loss [11,50]. By substituting Eq. (4) into Eq. (3), the total risk consequence of dam M in the cascade reservoirs is obtained, as shown in Eq. (5). Because of the uncertainty of successive dam breach, the segment losses are multiplied with the conditional probabilities.

$$CM = LMN + P(N|M) \times LNK + P(N|M) \times P(K|MN) \times LK \tag{5}$$

In the methodology above, the calculation of these conditional probabilities of successive dam breach takes into account all possible water level conditions of the cascade reservoirs. However, for the simulation of the inundation, it is unrealistic in practical application to simulate the dam-break flood under all possible water level conditions. Therefore, a suitable initial water level needs to be selected for the inundation analysis of the dam-break flood. For the reservoir to be evaluated, its water level at which the dam breach begins can be set by analyzing the possible dam failure mode [27]. Moreover, a higher of the water levels during the operation period of the downstream reservoir can be taken as its initial water level to reflect a dangerous situation. In short, specific analysis and demonstration should be combined with the reservoir operation law to make the simulated dam-break flood more representative.

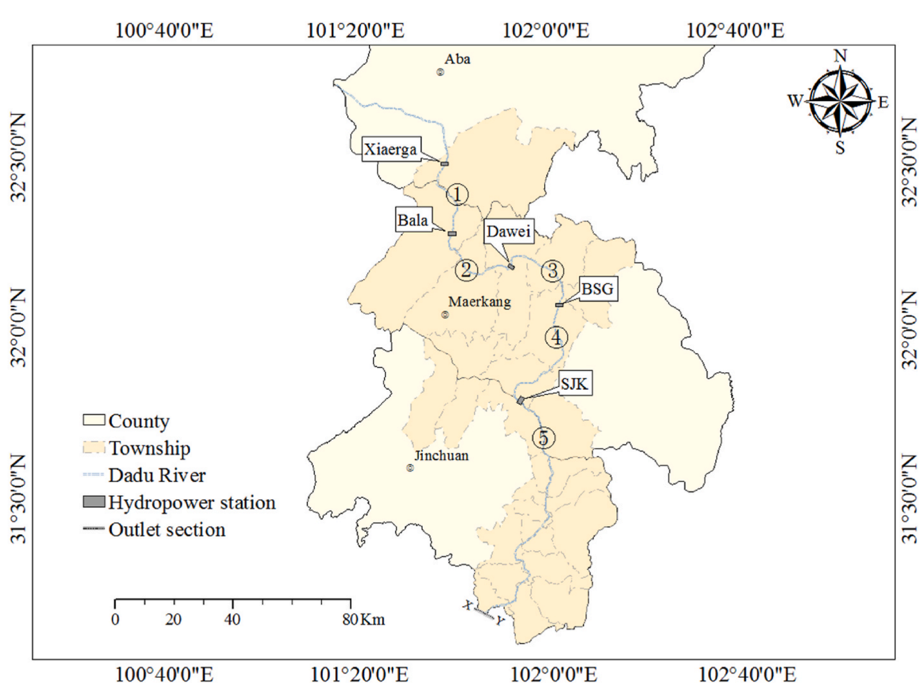



**Fig. 6.** Geographical location of the cascade reservoirs.

## 3. Results

### 3.1. Project overview

Five cascade reservoirs in the Dadu River Basin of China are selected as examples for analysis. The geographical locations and parameter datas of these cascade reservoirs are shown in Fig. 6 and Table 1, respectively. In view of the wide range of successive dam-break flood routing along the river, the study area is defined from the Xiaerga dam to the outlet section "X–Y" at the administrative boundary of Jinchuan county. The water levels in front of the dam during the operation period of the Bala, Dawei, BSG and SJK reservoirs followed the normal distribution of (3118, 1.4), (2920, 0.5), (2685, 0.7), (2599, 1.2) and (2498, 1.6), respectively. The former in brackets referred to the mean (meters), and the latter was the standard deviation, respectively [10,27]. To express the analysis process more clearly, the study area was divided into five segments from upstream to downstream, bounded by these cascade dams, shown in Fig. 6.

### 3.2. Determination of the conditional probability of successive dam breach

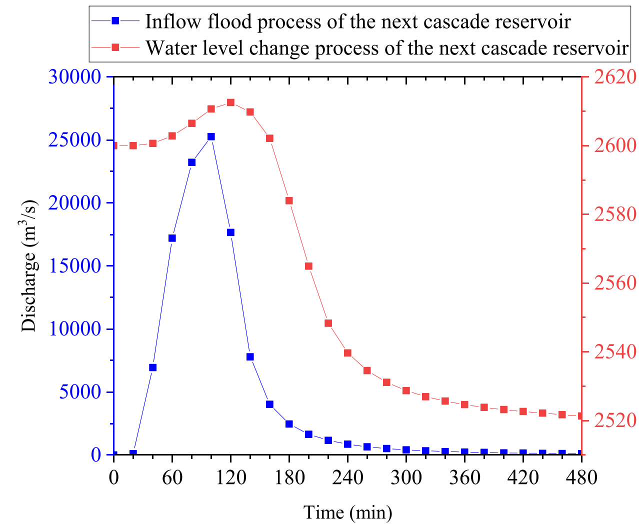
According to the comparison of the total capacities in Table 1, it can be inferred that the dam breach of Xiaerga Reservoir will inevitably lead to the successive dam breaches of all downstream cascade reservoirs. Hence, the conditional probabilities (CP) of various successive breaches caused by the dam-break flood of Xiaerga Reservoir were directly taken as 1. For other cascade dams, the CPs were calculated one by one according to the method described in Section 2.3. It is important to emphasize that all possible successive dam breach scenarios caused by each cascade dam were considered, and then a large number of reservoir water level combinations were sampled for each scenario to calculate the corresponding CPs.

The Dawei Reservoir was selected as an example. After the overtopping of Dawei Reservoir, its dam-break flood flowed into the downstream BSG Reservoir. When the normal pool level was sampled as the initial water level of BSG Reservoir, its inflow flood process and water level change process were calculated through dam breach simulation, as shown in Fig. 7 (a). It can be seen that under this scenario, the highest water level of BSG Reservoir exceeded the dam crest elevation, indicating that the dam-break flood of Dawei Reservoir caused the dam breach of BSG Reservoir. Subsequently, the successive dam-break flood of "Dawei-BSG" flowed into SJK Reservoir at the normal pool level, as shown in Fig. 7 (b). It can be seen that under this scenario, the highest water level of SJK Reservoir was lower than the dam crest elevation, indicating that the successive dam-break flood of Bala Reservoir did not cause the overtopping of SJK Reservoir.

According to the water level distributions of two adjacent cascade reservoirs, 10,000 groups of water level combinations were sampled in MATLAB. The analysis model of successive dam breach was carried out to obtain the random distribution of water level in front of the downstream cascade dam after superimposing the upstream dam-break flood [10]. The results of two scenarios were shown in Fig. 8. By repeating the above process, the number of overtopping under different dam breach scenarios were obtained and the corresponding CPs were determined, as shown in Table 2.

**Table 1**
Parameter data of the cascade reservoirs.

| Reservoir | Total capacity ($10^8$ $m^3$) | Dam crest elevation (m) | Normal pool level (m) | Checking flood level (m) | Dam height (m) |
|---|---|---|---|---|---|
| Xiaegra | 28 | 3125 | 3120 | 3122 | 233 |
| Bala | 1.28 | 2925 | 2920 | 2922 | 142 |
| Dawei | 1.4 | 2690 | 2686 | 2688 | 107 |
| BSG | 2.48 | 2608 | 2600 | 2603 | 133 |
| SJK | 28.97 | 2507 | 2500 | 2504 | 314 |



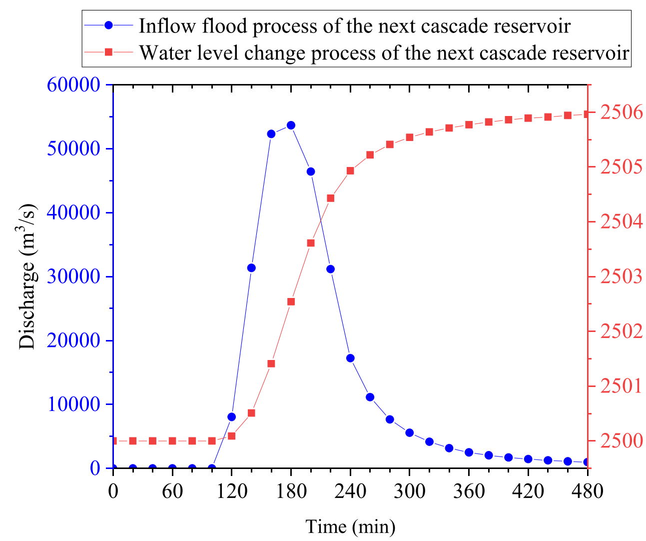




**Fig. 7.** The process of upstream dam-break flood in downstream reservoir. (a) Scenario of the breach of Dawei Reservoir; and (b)Scenario of the successive breach of "Dawei-BSG".

### 3.3. Simulation of dam breach inundation for different scenarios

Each of the five cascade reservoirs was subjected to a dam-break flood inundation simulation and the breach mode was set as overtopping. HEC-RAS software was used for dam breach simulation and flood routing analysis to obtain the maximum inundated area, water depth, velocity and other hydraulic indicators under the corresponding dam breach scenario. Considering the effects of various types of land on flood routing, the downstream terrain was divided into 50 m × 50 m computational grids and the Manning's coefficients was assigned [40, 51].

With the help of satellite map and data of different land use types in the study area [20], the distribution of residential area within the scope of dam-break flood inundation and different types of land inundation were obtained, which laid a foundation for risk consequence assessment. Several simulation results are shown in Figs. 9–11.

The four scenarios that dam breach of SJK (single cascade),

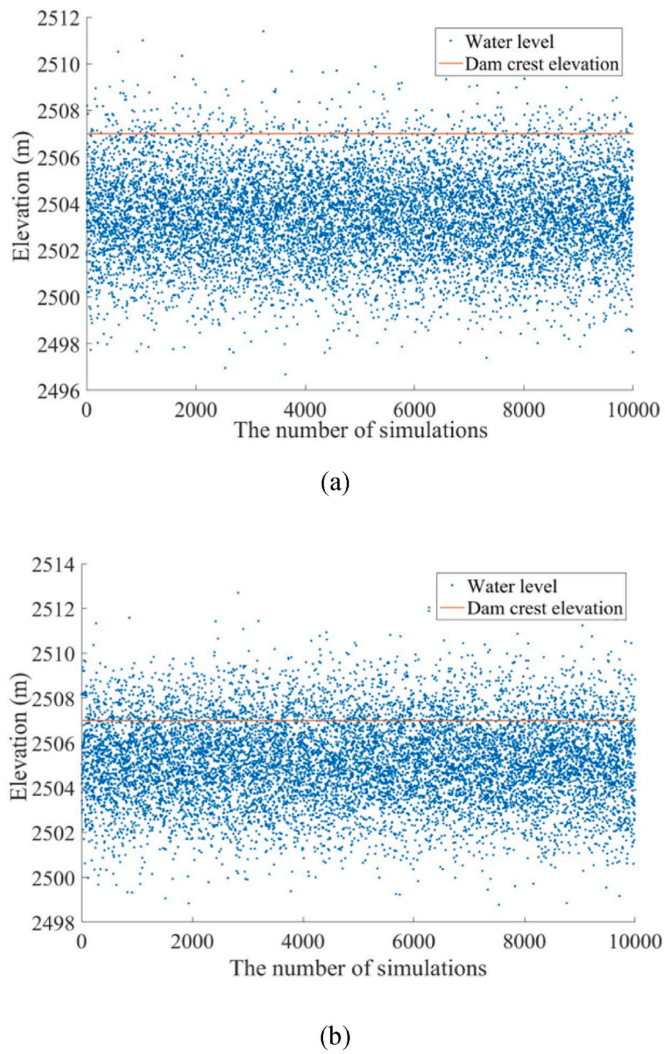



**Fig. 8.** Water level distribution in front of the dam of SJK Reservoir under different scenarios. (a) Scenario of the successive breach of "Dawei-BSG" and (b) Scenario of the successive breach of "BaLa-Dawei-BSG".

successive dam breach of "Dawei to SJK" (three cascades), successive dam breach of "Bala to SJK" (four cascades) and successive dam breach of "Xiaerga to SJK" (five cascades) were defined as Scenarios I-IV. The simulation showed that under these scenarios, the evolution times of the dam-break floods from SJK dam site to the most downstream Section X-Y in Fig. 4 was 240min, 236min, 233min and 227min, respectively. Taking the time when the flood peak reached this section as the starting point, the change process of flow and water level is shown in Fig. 12. As can be seen, with the increase of the number of cascades, the time of successive dam-break flood routing to the downstream section was earlier, the peak flow, water level and the inundation duration were much larger than the dam-break flood of a single reservoir.

### *3.4. Inundation loss statistics and risk consequence calculation of cascade dam breach*

According to the concept in Fig. 2, the difference between the maximum inundation loss under each dam breach scenario and the original inundation of the downstream reservoir was taken as the value of the corresponding dam-break flood inundation loss. Considering the huge impact of successive dam-break flood and the fact that the inundated area was in a deep valley, which was not conducive to emergency evacuation, the actual resident population in the inundated area was taken to reflect the life loss [11,20]. The inundated population can be quantified based on the population density layer of the inundated area [52]. The inundation areas of different land use types obtained by the product of grid area and number were taken as reference indexes to measure the impact of dam-break flood on the downstream land for further research.

Each cascade dam breach first causes a part of direct inundation, if it causes the successive breach of downstream cascades, the inundation range will continue to expand and the segmented inundation loss will be generated in the corresponding segments. As the dam breach scenario of Bala Reservoir shown in Fig. 13, the red frame points to its direct inundation, the blue, green and yellow frames point to the three segmented inundation respectively. The statistics of inundation loss under each dam breach scenario are shown in Table 3.

According to the calculation method in Section 2.5, the total risk consequences of each cascade dam breach were calculated by combining the segmented inundation loss and the conditional probabilities of successive dam breach, respectively. Taking Bala reservoir as an example, the direct inundated population after its breach was 473 persons and the potential inundated population was 7697 persons ($PC = 1 \times 612 + 1 \times 1 \times 380 + 1 \times 1 \times 0.177 \times 37{,}884$). Therefore, the dam breach risk consequence of Bala Reservoir was an inundated population of 8170 persons. The calculation results of dam breach risk consequences of the five cascade reservoirs are shown in Table 4.

**Table 2**
Calculation of the $CP_S$ after 10,000 simulations under different dam breach scenarios.

| Cascade reservoir | Possible scenario of dam breach | The next adjacent cascade | Number of simulations | Number of overtopping of the next adjacent cascade | CP |
|---|---|---|---|---|---|
| Xiaerga | Single dam breach of Xiaerga | Bala | No simulation required | No simulation required | 1 |
| | Successive breach of "Xiaerga-Bala" | Dawei | | | 1 |
| | Successive breach of "Xiaerga-Bala-Dawei" | BSG | | | 1 |
| | Successive breach of "Xiaerga-Bala-Dawei-BSG" | SJK | | | 1 |
| Bala | Single dam breach of Bala | Dawei | 10,000 | 10,000 | 1 |
| | Successive breach of "Bala-Dawei" | BSG | 10,000 | 10,000 | 1 |
| | Successive breach of "Bala-Dawei-BSG" | SJK | 10,000 | 1769 | 0.177 |
| Dawei | Single dam breach of Dawei | BSG | 10,000 | 1 | 1 |
| | Successive breach of "Dawei-BSG" | SJK | 10,000 | 358 | 0.036 |
| BSG | Single dam breach of BSG | SJK | 10,000 | 0 | 0 |

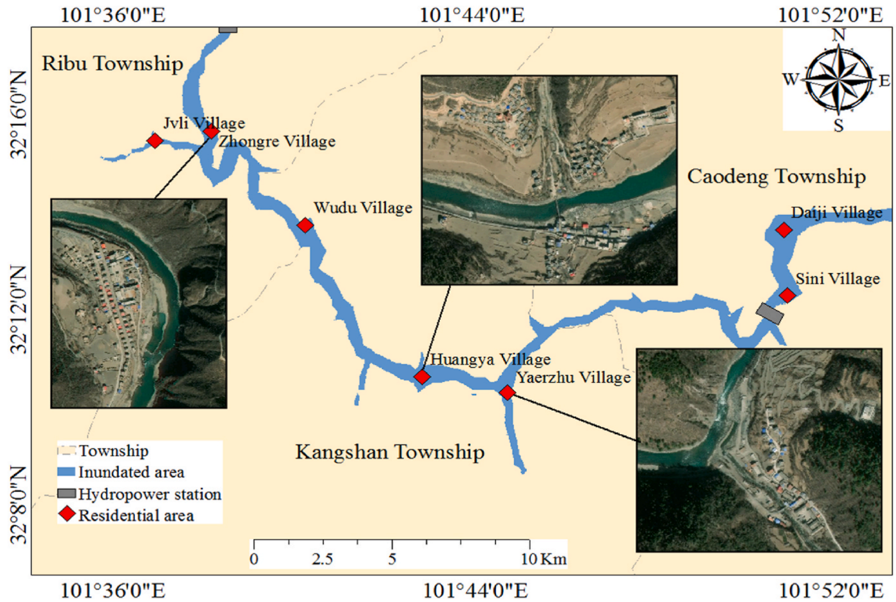



**Fig. 9.** Inundated residential area under the dam breach scenario of Xiaerga Reservoir.

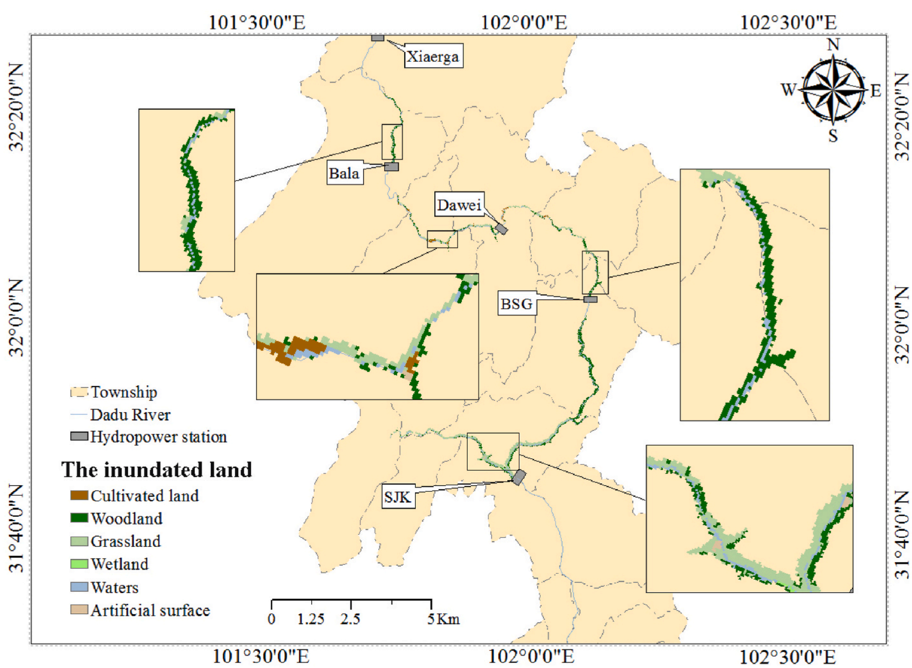



**Fig. 10.** The original inundated land area of the cascade reservoirs.

## 4. Discussion

According to Table 2, the overtopping of Xiaerga Reservoir would directly lead to the successive breach of all downstream cascades. Thus, the difference between the inundation loss of the successive dam-break flood and the original inundation of the downstream reservoirs was directly taken as the value of its dam breach risk consequence; For the two reservoirs, Bala and Dawei, there was uncertainty about whether their breachs would lead to successive breach of the downstream cascades, so the dam breach risk consequence of these two reservoirs were divided into *DC* and *PC* separately. The overtopping of BSG Reservoir would not cause the dam breach in downstream adjacent cascade, its risk consequence was equal to the difference between the dam breach inundation loss and the original inundation of SJK Reservoir; SJK Reservoir was located in the most downstream of the cascade reservoir group, its risk consequence was the downstream inundation loss of its own breach.

It can be seen from Eq. (5) and Table 4 that the conditional probability determined how much segmented inundation loss became the *PC* of the dam breach risk consequence. If a cascade dam breach does not have the potential to cause the successive dam breach of its downstream cascade, as in the case of the BSG Reservoir, the risk consequences is only *DC*. Therefore, the conditional probability can effectively quantify the risk transmission and superposition effect in the dam breach risk consequence assessment of cascade reservoirs. In engineering applications, the conditional probability of successive dam breach can be reduced by measures such as increasing the flood control capacity of the downstream cascade reservoirs, thereby reducing the dam breach risk

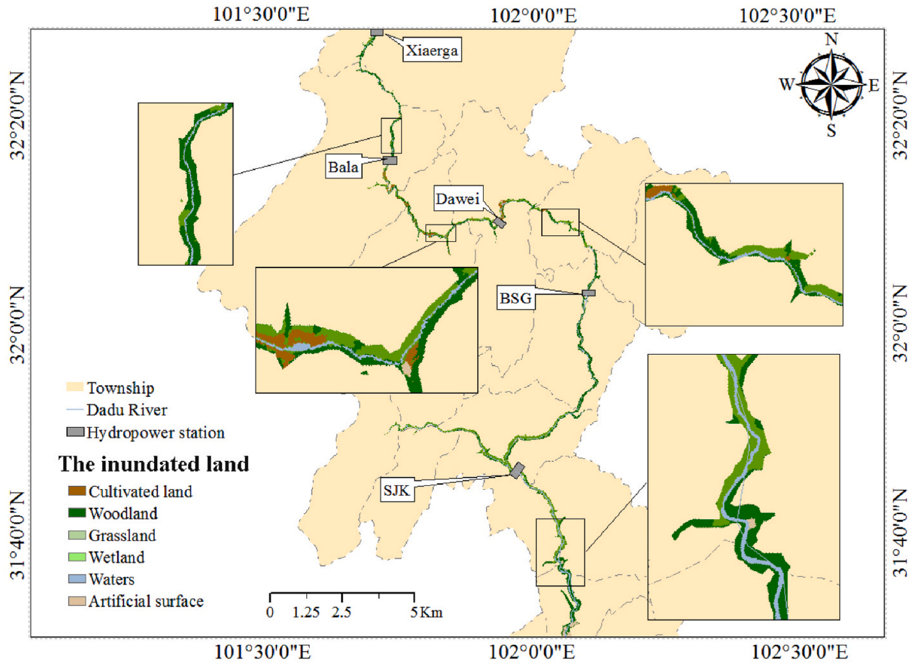



**Fig. 11.** Inundated land area under the dam breach scenario of Xiaerga Reservoir.

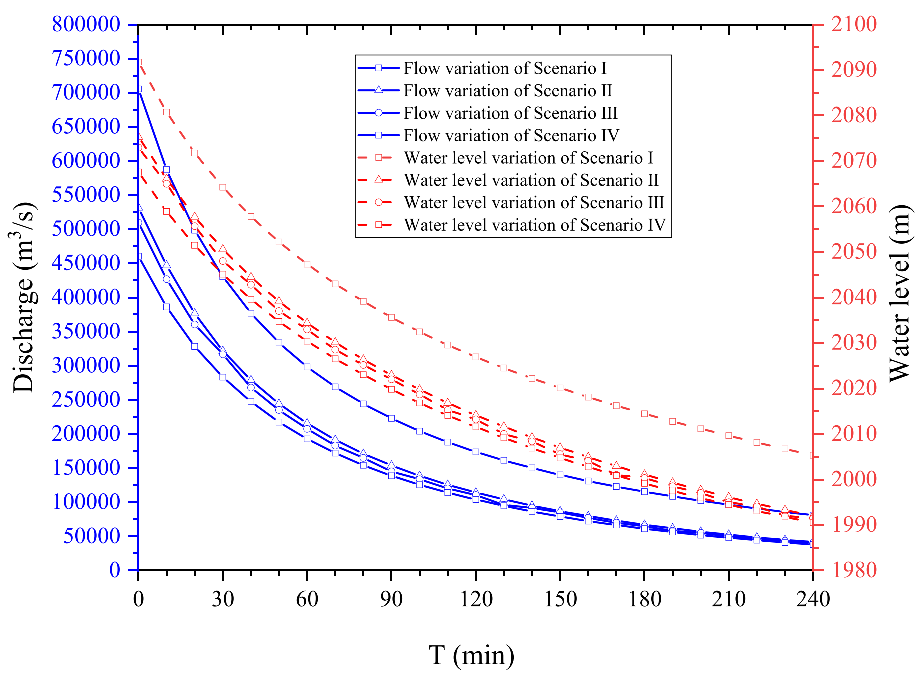



**Fig. 12.** Variation process of discharge and water depth of X–Y section under different successive dam breach scenarios.

consequence [35].

For Bala Reservoir and Dawei Reservoir, the total value of inundated population and land area of dam breach in Table 3 were obtained by directly superimposing the segmented inundation loss, which were significantly different from the results in Table 4 that combined with the successive dam breach probabilities. The former directly attributed the successive dam-break flood inundation to the total loss of upstream cascade, it was considered that the upstream cascade dam breach would inevitably lead to the successive dam breach of all downstream cascades, which exaggerated its risk consequence. In fact, one of the requirements of risk assessment is to effectively express the uncertainty of risk in quantitative calculation [53]. Therefore, the assessment results in Table 4 are more reasonable and more in line with the connotation of dam risk management.

This study mainly focused on the risk consequence assessment method of dam breach in cascade reservoirs under the action of risk transmission and superposition. By comparing the assessment results, it will be clear which cascade reservoir requires the most attention to avoid the most adverse consequence. To simplify, the inundated population and land area were taken as example indicators to reflect the dam breach consequence. In the future research, the itemized losses of dam breach can be further analyzed in detail according to the assessment method of general ordinary reservoir dams [54-56]. In addition, the dam breach risk consequence assessment model constructed in this paper

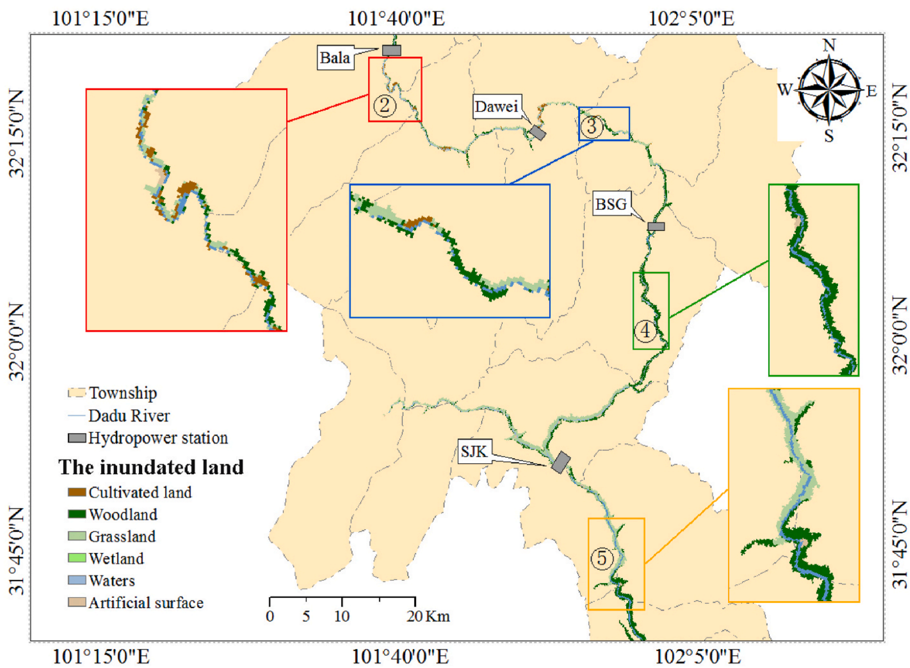



**Fig. 13.** The segmented land inundation under the dam breach scenario of Bala Reservoir.

**Table 3**
Statistics of inundation loss of each cascade dam breach.

| Cascade reservoir | | Xiaerga | Bala | | | | Dawei | | | BSG | SJK |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Item | | Inundation loss | Direct inundation | Segmented inundation | | | Direct inundation | Segmented inundation | | Inundation loss | Inundation loss |
| Segment | | ① ② ③ ④ ⑤ | ② | ③ | ④ | ⑤ | ③ | ④ | ⑤ | ④ | ⑤ |
| Inundated population (persons) | | 402,690 | 473 | 612 | 380 | 37,884 | 508 | 380 | 37,562 | 678 | 37,324 |
| Sum | | | 39,349 | | | | 38,450 | | | | |
| Inundated area ($1000m^2$) | Cultivated land | 74947.8 | 905.3 | 401.3 | 0 | 2560.1 | 298.7 | 0 | 2550.4 | 0 | 2540.8 |
| | Woodland | 857147.2 | 1148 | 541.3 | 1782.6 | 40043.7 | 448 | 1707.9 | 39473.7 | 1516.7 | 38758.8 |
| | grassland | 472698.9 | 1427.9 | 578.6 | 494.6 | 19765.8 | 429.3 | 494.6 | 19543.6 | 415.4 | 19186.2 |
| | Wetland | 2241.3 | 0 | 0 | 0 | 106.3 | 0 | 0 | 106.3 | 0 | 106.3 |
| | Waters | 299540.2 | 765.3 | 149.3 | 616 | 16944.9 | 74.7 | 606.6 | 16915.9 | 637.6 | 16915.9 |
| | Artificial surface | 159923.5 | 140 | 74.7 | 196 | 13959.7 | 46.7 | 196 | 13863.1 | 135.3 | 13679.6 |
| | Sum | 1866498.9 | 4386.5 | 1745.3 | 3089.2 | 93380.5 | 1297.3 | 3005.2 | 92453.1 | 2705 | 91187.5 |
| | | | 102601.5 | | | | 96755.6 | | | | |

**Table 4**
The total risk consequence calculation of each cascade dam breach.

| Cascade reservoir | | Xiaerga | Bala | | Dawei | | BSG | SJK |
|---|---|---|---|---|---|---|---|---|
| Item | | *TRC* | *TRC* | | *TRC* | | *TRC* | *TRC* |
| | | | *DC* | *PC* | *DC* | *PC* | | |
| Inundated population (persons) | | 40,269 | 473 | 7697 | 508 | 1732 | 678 | 37,324 |
| Sum | | | 8170 | | 2240 | | | |
| Inundated area ($1000m^2$) | Cultivated land | 74947.8 | 905.3 | 854.5 | 298.7 | 91.8 | 0 | 2540.8 |
| | Woodland | 857147.2 | 1148 | 9411.6 | 448 | 3129 | 1516.7 | 38758.8 |
| | Grassland | 472698.9 | 1427.9 | 4571.8 | 429.3 | 1198.2 | 415.4 | 19186.2 |
| | Wetland | 2241.3 | 0 | 18.8 | 0 | 3.8 | 0 | 106.3 |
| | Waters | 299540.2 | 765.3 | 3764.5 | 74.7 | 1215.6 | 637.6 | 16915.9 |
| | Artificial surface | 159923.5 | 140 | 2741.5 | 46.7 | 695.1 | 135.3 | 13679.6 |
| | Sum | 1866498.9 | 4386.5 | 21362.8 | 1297.3 | 6333.5 | 2705 | 91187.5 |
| | | | 25749.3 | | 7630.8 | | | |

where the "*TRC* " represents "the total risk consequence of dam breach".

included the consideration of the reservoir original inundation, so it was also suitable for the inundated losses calculation in the reservoir planning and design stage, which provided a reference for the selection of reservoir design scheme.

## 5. Conclusions

Owing to the risk transmission and superposition, a cascade dam breach has the potential to trigger the successive dam breaches in the downstream cascades, resulting in the uncertainty of the successive breach scenarios and the impact areas. Thus, the dam breach risk consequence assessment methods for a single reservoir has limitations in the analysis of cascade reservoirs. In this study, the risk consequence of dam breach in cascade reservoirs was decomposed into *DC* and *PC*, which makes the impact scope of a cascade dam breach intuitive and reduces the complexity of its risk consequence analysis from the spatial level. Through the analysis of risk correlation, it was proved that the conditional probability of successive dam breach is feasible to quantify the risk transmission and superposition effect in cascade reservoirs. Furthermore, the calculation formulas of dam breach risk consequence in cascade reservoirs were proposed. Finally, five cascade reservoirs were selected for example analysis, and the inundated population and land area under each dam breach scenario were calculated. It was concluded that the total dam breach risk consequence of Xiaerga Reservoir was the most severe. Compared with directly adding all the segmented inundation loss, the assessment method proposed in this paper is more scientific and reasonable to measure the risk consequence, which can provide theoretical support for the risk assessment and management of cascade reservoirs.

## Credit author statement

Conceptualization, T.W. and Z.L.; Methodology, T.W. and W.G.; Validation Z.L. and W.G.; Formal analysis, Y.Z. and H.S.; Investigation, H.Z. and Y.J; Writing – original draft, T.W.; Writing – review & editing, T.W. and W.G.; Supervision, Z.L.; Funding acquisition, Z.L. and W.G.

## 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.

## Acknowledgements

This research was funded by the National Natural Science Foundation of China (Grant No. 52179144, 52079127, U2243244, U2040224, 51679222), Program for Science&Technology Innovation Talents in Universities of Henan Province (HASTIT) (Grant No. 22HASTIT011), the Young Talent Support Project of Henan Province (Grant No. 2021HYTP024), the First Class Project of Yellow River Laboratory of Zhengzhou University (Grant No. YRL22IR03, YRL22LT06), and the Fund of National Dam Safety Research Center (Grant No. CX2021B01).

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