Risk-Based Warning Decision Making of Cascade Breaching of the Tangjiashan Landslide Dam and Two Smaller Downstream Landslide Dams

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Mega earthquakes or serious rainfall storms often cause crowded landslides in mountainous areas. A large part of these landslides are very likely blocking rivers and forming landslide dams in series along rivers. The risks of cascading failure of landslide dams are significantly different from that of a single dam. This paper presented the work on risk-based warning decision making on cascading breaching of the 2008 Tangjiashan landslide dam and two small downstream landslide dams in a series along Tongkou River. The optimal decision was made by achieving minimal expected total loss. Cascade breaching of a series of landslide dams is more likely to produce a multi-peak flood. When the coming of the breaching flood from the upstream dam perfectly overlaps with the dam breaching flood of the downstream dam, a higher overlapped peak flood would occur. When overlapped peak flood occurs, the flood risk would be larger and evacuation warning needs to be issued earlier to avoid serious life loss and flood damages. When multi-peak flood occurs, people may be misled by the warning of the previous peak flood and suddenly attacked by the peak flood thereafter, incurring catastrophic loss. Systematical decision making needs to be conducted to sufficiently concern the risk caused by each peak of the breaching flood. The dam failure probability P_f linearly influences the expected life loss and flood damage but does not influence the evacuation cost. The expected total loss significantly decreases with P_f when the warning time was insufficient. However, it would not change much with P_f when warning time is sufficient.

Keywords: landslide dam, cascade dam breaching, risk assessment, warning, decision making

INTRODUCTION

Mega earthquakes or serious rainfall storms often cause crowded landslides in mountainous areas. A large part of these landslides are very likely blocking rivers and forming landslide dams in series along rivers. For instance, a heavy storm in 1889 triggered at least 28 landslide dams in Totsukawa, Japan (Tong, 2008); the 2004 Ms 6.8 Mid Niigata Prefecture Earthquake in Japan

formed 45 landslide dams; the Typhoon Morakot in 2009 induced 19 landslide dams in Taiwan (Dong et al., 2011; Wang et al., 2016); and the 2008 Ms 7.9 Wenchuan earthquake triggered as large as 257 landslide dams (Cui et al., 2009). Many of these landslide dams were formed in series along rivers, including the Tangjiashan landslide dam, the largest one caused by the 2008 Wenchuan earthquake, and two relatively small landslide dams downstream along the Tongkou River (Cui et al., 2010; Liu et al., 2010; Shi et al., 2015). A dam failure upstream could cause outburst of water flow, leading to dam failures downstream one after another, an enormous flash flood, and serious damage downstream. Such a failure of a series of dams is called cascading failure.

Despite of many studies on breaching of a single man-made earthen embankment dam (ASCE/EWRI Task Committee on Dam/Levee Breaching, 2012) and a single landslide dam (Peng and Zhang, 2012a; Shen et al., 2020), the corresponding studies cascading dam breaching are much less. Cui et al. (2013); Zhu et al. (2012), and Zhou et al. (2013) investigated the Zhouqu debris flow in 2010 in China and conducted field tests on cascading dam breaching involving several model dams. Cao et al. (2011) compared the breaches of a single dam and two dams in a series through experimental study and numerical analysis. Niu et al. (2012) conducted an experimental investigation of the failure of a single dam and cascade landslide dams with different inflow rates. Shi et al. (2015) improved the DABA model (Chang and Zhang, 2010; Peng et al., 2014) to simulate the Tangjiashan landslide dam and two small landslide dams downstream. Since the DABA 2.0 model is validated with well-recorded cases, it is applied for cascade breaching of landslide dams in this study.

Risk assessment of landslide dam breaching is of great significance for decision making of emergency measures (Dong et al., 2011; Chen et al., 2017; Nibigira et al., 2018). The existing studies on risk assessment can be divided into two types: qualitative and quantitative risk assessment.

In qualitative risk assessment, Cui et al. (2009); Xu et al. (2009), and Yang et al. (2013) ranked the risk of a landslide dam based on some easily accessible parameters. Wang and Liu (2013); Xu et al. (2017), and Liao et al. (2018) ranked the landslide dam risk according to the subjective scours via fuzzy comprehensive methods. Qualitative risk assessment methods are efficient to get a general understanding of a landslide dam. However, they are not sufficient for scientific decision making to balance the costs and gains under different mitigation measures (Peng et al., 2014; Juang et al., 2019).

In quantitative risk assessment, Peng and Zhang (2012b,c) presented a human risk assessment method (HURAM) by using Bayesian networks. It was able to take into account a large number of important parameters and their interrelationships in a systematic structure including their uncertainties. On the basis of HURAM, Shi et al. (2017) developed an efficient method for rapid and quantitative risk assessment of landslide dams via GIS technique. The method was applied to the Hongshiyan landslide dam triggered by the 2014 Ludian earthquake.

With quantitative risk assessment, optimal decision making could be achieved by minimizing the expected total loss. The decision tree is an effective tool for risk-based decision making.

Frieser (2004) presented a multistep decision tree to achieve the optimal time for warning decision making on levee failure, with which the decision could be delayed for gaining more precise information to reduce the uncertainty. Smith et al. (2006) proposed a probabilistic approach to evacuation decision-making using a distributed rainfall–runoff model based on the decision tree. Wu et al. (2010) presented a risk analysis model to evaluate the risk of underestimating the predicted peak discharge during the flooding prevention and warning operation. Su et al. (2011) developed an early warning system of dam health with systems engineering (integration control module, intelligent inference engine, support base cluster, etc.) and artificial intelligent methods. Peng and Zhang (2013a,b) built a dynamic risk decision-making model, DYDEM, using the time-series analysis method to predict the dynamic probability of dam breaching and the Bayesian network method to estimate the flood losses. Fan et al. (2018) conducted early warning of flood-affected areas when a dam break occurred in a mountain river via the fuzzy analytic hierarchy process (FAHP).

Despite that some efforts have been made for risk assessment and decision making on dam breaching floods, the corresponding studies on cascading breaching of landslide dams are seldom found. In cascading dam breaching, multi-peak floods are very likely to occur. The influence of the former peak flood on the decision for the latter peak flood is not sufficiently investigated. Moreover, the problems on risk-based warning decision making for the overlapped peak flood with amplification effects remain unsolved.

This paper conducted risk-based warning decision making on cascading breaching of the Tangjiashan landslide dam and two small downstream landslide dams (the Kuzhuba and Xinjiecun landslide dams) in a series along Tongkou River. Four scenarios were considered: the real case with the constructed spillway, a virtual case without the spillway, and two more virtual cases with amplified floods by considering the overlapping effect on the basis of the first two scenarios (Shi et al., 2015). First, cascading breaching of the three landslide dams was simulated with a dam breaching model of DABA 2.0. Second, flood routing of dam breaching was conducted by HEC-RAS software. Third, a quantitative risk assessment on the dam breaching flood in Beichuan County and Mianyang City, which were 4.5 and 85 km downstream of the Tangjiashan landslide dams, respectively, was made by using the HURAM model. Finally, optimal decision making on warning and evacuation of the population at risk was made to minimize the expected total loss, which consists of evacuation costs, monetized life loss, and economic loss. Note that despite of the ethical considerations, a human life has to be measured for evacuation decision making. A method with macroeconomic considerations is chosen in this study (Jonkman, 2007).

METHODOLOGY

The method of risk-based warning decision making on cascade breaching of landslide dams consists of four components: (1) cascade breaching modeling of landslide dams with the modified

DABA model (Shi et al., 2015); (2) flood routing simulation after cascade dam breaching using HEC-RAS (Hydraulic Engineering Center, 2008); (3) quantitative risk assessment considering multi-peak floods with the HURAM model (Peng and Zhang, 2012b,c); and (4) warning decision making to minimize the expected total loss.

Cascade Dam Breach Modeling With the Modified DABA Model

The cascading dam breaches can be divided into three components: dam breaching upstream, flood routing, and dam breaching downstream. The procedure repeats when there are more landslide dams downstream. Normally, the outburst of inflow caused by a dam failure upstream would result in full-section overflow of the downstream dam, leading to erosion both inside the breach and in the crest of the dam. The DABA model (Chang and Zhang, 2010) was modified by Shi et al. (2015) as DABA 2.0 to simulate the cascading breaching of landslide dams and validated with recorded data. In DABA 2.0, the inflow rates are set as a time-related variable instead of some piecewise constant values; the cross section was divided into three parts: left crest, breach, and right crest to simulate the overflow and erosion. The outflow rate was calculated as the sum of the outflow rate across the breach and two parts of dam crests:

$$Q = Q_l + Q_b + Q_r = 1.7A_l\sqrt{H - Z_l}$$
$$+ 1.7A_b\sqrt{H - Z_b} + 1.7A_r\sqrt{H - Z_r} \quad (1)$$

where A_l, A_b, and A_r are the cross-section areas of the water above the left dam crest, breach, and right dam crest, respectively; H is the water elevation; and Z_l, Z_b, and Z_r are the elevation of the left dam crest, breach bottom, and right dam crest, respectively.

The erosion rate E (eroded depth in a unit time) was calculated as (Chang and Zhang, 2010):

$$E = K_d (\tau - \tau_c) \quad (2)$$

where τ is the shear stress at the soil/water interface, which denotes the erosion ability; K_d is the coefficient of erodibility; τ_c is the critical shear stress at initiation of soil erosion; and K_d and τ_c represent the erosion resistance of soils, which can be estimated using empirical equations (Chang and Zhang, 2010).

Flood Routing Simulation With HEC-RAS

HEC-RAS is a typical model for flood routing which is developed by the United States Army Corps of Engineers (Hydraulic Engineering Center, 2008). The flood routing path is divided into river channel and floodplains with different Manning's n values. Digital elevation models of the landslide dams and the Tongkou and Fujiang Rivers were input into the HEC-RAS to form a numerical model. The breaching outflow rate of the upstream dam was input as the boundary condition in HEC-RAS. The Manning's n values of the river are obtained according to Chow (1959).

Dam breaching flood routing was simulated as unsteady flow via HEC-RAS. The physical laws that govern the unsteady flow are the principle of conservation of mass and momentum. The

governing equation for the principle of conservation of mass is expressed as (Hydraulic Engineering Center, 2008).

$$\frac{\partial A_T}{\partial t} + \frac{\partial Q}{\partial x} - q_l = 0 \quad (3)$$

where A_T is the total flow area, Q is the flow rate, x is the length of the channel, and q_l is the lateral inflow per unit length.

The governing equation for the principle of conservation of mass is expressed as (Hydraulic Engineering Center, 2008).

$$\frac{\partial Q}{\partial t} + \frac{\partial Qv}{\partial x} + gA\left(\frac{\partial z}{\partial x} + S_f\right) = 0 \quad (4)$$

where v is the flow velocity, A is the flow area, and z is the water surface. These laws are expressed mathematically in the form of partial differential equations in HEC-RAS (Hydraulic Engineering Center, 2008).

Quantitative Risk Assessment With the HURAM Model

Based on the definition of risk (Ang and Tang, 2007), the human risk (R_{human}) of dam-break floods is calculated as:

$$R_{human} = \sum PAR_i \times P_i \quad (5)$$

where PAR_i and P_i are the population at risk and the probability of loss of life for subarea i, respectively. HURAM is applied to obtain P_i in this study.

Human risk assessment method is a dam-break risk assessment model by using the Bayesian network analysis method. The Bayesian network in HURAM consists of 15 nodes (parameters) and 23 arcs (interrelationships between parameters) as shown in **Figure 1**. The prior (conditional) probability matrix was quantified with statistical data, existing physical models, empirical models, and judgment. HURAM works by updating the prior probabilities with evidence from a specific case using Bayes' theory (Peng and Zhang, 2012a,b). With the hydraulic parameters obtained by DABA and HEC-RAS, the probability of evacuation and fatality can be achieved by Bayesian updating.

According to the Bayesian network, the joint probability $P(X_1, X_2, \ldots, X_n)$ can be expressed as the products of the conditional probability of each node given to its parents (Jensen, 2001):
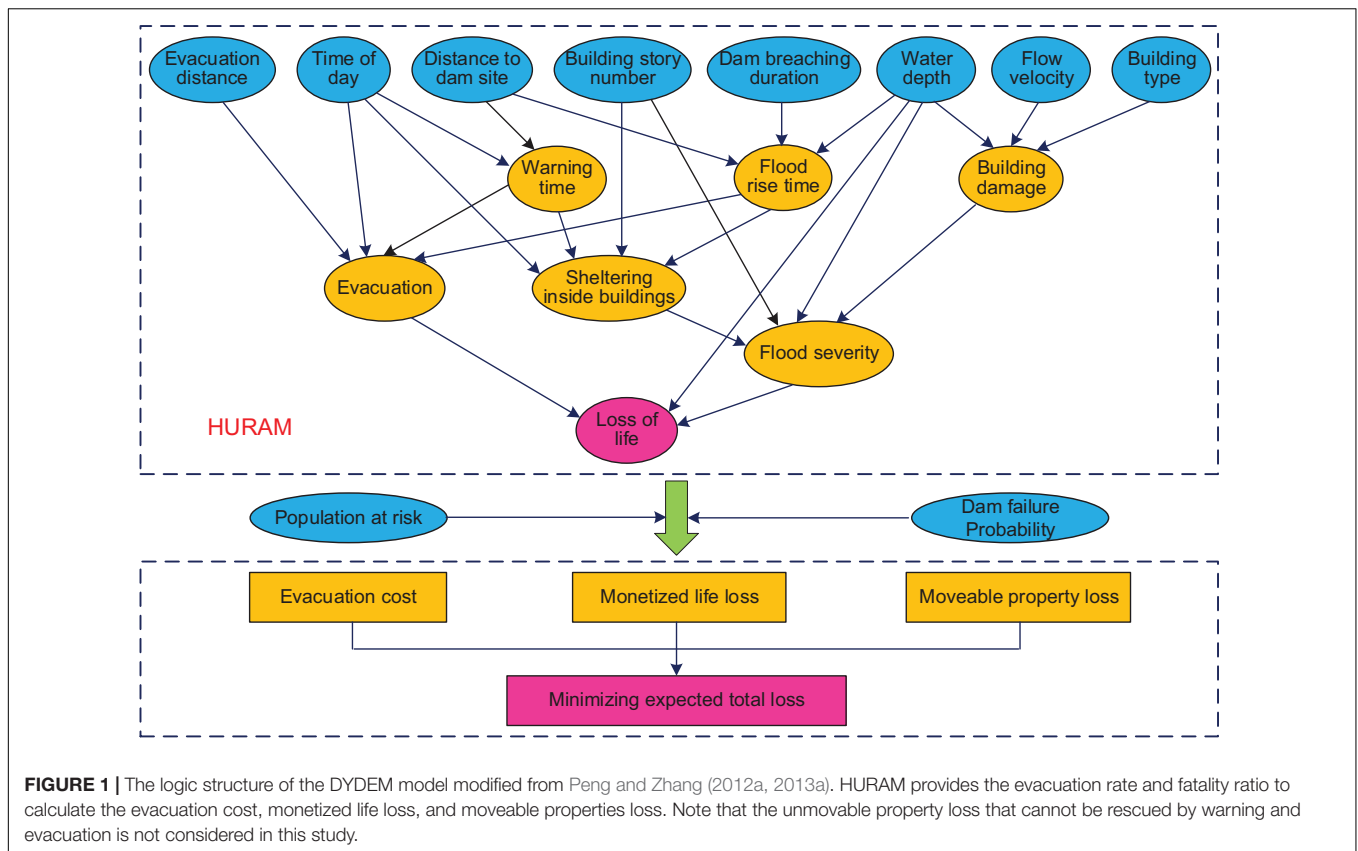
$$P(X_1, X_2, \ldots, X_n) = \prod_{i=1}^{n} P(X_i | \pi(X_i)) \quad (6)$$

where $\pi(X_i)$ is the set of all the parents of X_i, or the nodes that directly affect X_i. For the discrete state Bayesian network, the basic parameters of a Bayesian network are expressed as (Zhang and Guo, 2006):

$$\theta_{ijk} = P(X_i = k | \pi(X_i) = j) \quad (7)$$

where k and j are the state number of the node X_i and its parents. According to the Bayesian theory, the posterior probability of the parameter vector is given by Zhang and Guo (2006):

$$P(\theta | D) \propto P(\theta) \prod_{i=1}^{n} \prod_{j=1}^{q_i} \prod_{k=1}^{r_i} \theta_{ijk}^{m_{ijk}} \quad (8)$$

FIGURE 1 | The logic structure of the DYDEM model modified from Peng and Zhang (2012a, 2013a). HURAM provides the evacuation rate and fatality ratio to calculate the evacuation cost, monetized life loss, and moveable properties loss. Note that the unmovable property loss that cannot be rescued by warning and evacuation is not considered in this study.

Two major components in HURAM are to calculate the evacuation rate and fatality rate. The evacuation rate is defined as the probability of the successful evacuation when the available time (A_t) is larger than the demand time (D_t):

$$P_{eva} = P(A_t > D_t) \qquad (9)$$

where the available time consists of warning time (W_t) and flood rise time (R_t):

$$A_t = W_t + R_t \qquad (10)$$

The demand time consists of warning transmitting time (T_t), response time (R_t), and evacuation time (E_t):

$$D_t = T_t + S_t + E_t \qquad (11)$$

The distributions of the random variables in Equations (9)–(11) are suggested based on statistical data according to Peng and Zhang (2012b).

The fatality rate was suggested as a lognormal distribution as a function of water depth (Peng and Zhang, 2012b):

$$Fr(h) = \Phi\left(\frac{\ln(h) - \mu_N}{\sigma_N}\right) \qquad (12)$$

where $\mu_N = 1.649$ and $\sigma_N = 0.562$ for medium flood severity, and $\mu_N = 3.376$ and $\sigma_N = 1.188$ for low flood severity. $Fr(h)$ was set as a constant value of 0.918 for high flood severity.

Risk-Based Warning Decision Making

The optimal warning decision is achieved by minimizing the expected total loss L_T, which is calculated as Zhang et al. (2016):

$$L_T = C + P_f(D_M + M_L) \qquad (13)$$

where C denotes the evacuation cost; P_f denotes the failure probability of the landslide dam; D_M denotes the movable flood damage since the unmovable damage cannot be mitigated by warning and evacuation; and M_L denotes monetized life loss.

The evacuation cost C is the sum of the initial costs (C_i) and GDP interruption (C_{GDP}) (Peng and Zhang, 2013a). The initial costs (C_i) are the expenses for the evacuated people, such as temporary resettlement fee (e.g., accommodation, food, and compensation) and public maintenance fee (e.g., security and medical care). C_i is assumed proportional to the number of evacuated people and the interrupted time (Peng and Zhang, 2013a):

$$C_i = cP_{eva}P_{AR}(W_t + 3) \qquad (14)$$

where c is the expense per person per day (i.e., RMB60 in 2008 in Mianyang City according to Peng and Zhang, 2013a); P_{eva} is the proportion of the evacuated people, which is estimated using the modified HURAM; and W_t is the warning time in days. The 3-day time is the addition time for preparing the return of the residents (Frieser, 2004). C_{GDP} proportional to the number of the evacuated people, the GDP

per capita, and the interrupted time is shown as follows (Peng and Zhang, 2013a):

$$C_{GDP} = \frac{GDP_p}{365} P_{AR}(W_t + 4) \qquad (15)$$

where GDP_p is the GDP per capita in the flooded area (i.e., RMB 13,745 in 2008 in Mianyang City according to Mianyang Bureau of Statistics, 2008). A duration of 4 days is added into the interrupted time for one more day to restart their business after the residents returning.

The moveable flood damage D_M is assumed proportional to the number of the people who neither evacuated nor sheltered in safe zones (in the building story beyond the inundation height) (Peng and Zhang, 2013a):

$$D = (1 - P_{eva})(1 - P_{safe})P_{AR}\alpha I_p \qquad (16)$$

where P_{safe} is the probability of the people taking shelter in safe zones, which is obtained via HURAM; α is the average proportion of the moveable property per person (0.1 is assumed); and I_p is the property per person (i.e., RMB 44,800 in 2008 in Mianyang City according to Mianyang Bureau of Statistics, 2008).

Despite ethical considerations, a life is measured for rational decision making. Jonkman (2007) reviewed the methods of evaluating the human life and suggested a method with macroeconomic considerations. In this method, the value of a human life (V_L) is calculated as the product of the GDP per person (GDP_p) and the average longevity (L):

$$V_L = GDP_p L \qquad (17)$$

For instance, the GDPp and L in Mianyang City in 2008 were RMB 13,745 and 75 years, respectively (Mianyang Bureau of Statistics, 2008). Thus, the V_L is RMB 1.03 million.

The monetized life loss (M_L) is calculated as:

$$M_L = V_L P_{AR} P_{LOL} \qquad (18)$$

where P_{LOL} is the probability of life loss, which can be achieved via HURAM as shown in **Figures 2**, **3**. If political or societal influences are involved, which puts saving a life as the highest priority, new criteria should be used. In this case, the human risk should be first reduced to a certain degree before considering economic issues.

DAM BREACHING AND FLOOD ROUTING SIMULATION

Introduction of the Three Landslide Dams

The 2008 Ms 8.0 Wenchuan earthquake triggered as many as 257 landslide dams in Sichuan Province, China, most of which formed in series along rivers. The Tangjiashan landslide dam and two smaller downstream landslide dams (Kuzhuba and Xinjiecun landslide dams) were typical cases of this type (**Figure 4**). The Tangjiashan landslide dam, which was of the highest risk and concern at that time, had a height of 82 m and a lake capacity

of 316×10^6 m^3 as shown in **Figure 4**; Hu et al., 2009; Cui et al., 2009; Chang and Zhang, 2010). The Kuzhuba and Xinjiecun landslide dams, which were formed 2.0 and 3.5 km downstream of the Tangjiashan dam, had heights of 60 and 20 m, and lake volumes of 18 and 2 million m^3, respectively (Zhang, 2009; Liu et al., 2010; Shi et al., 2015). The detailed information of these three dams is shown in **Table 1**.

The coefficient of erodibility of the Tangjiashan landslide dam varied from 120 mm^3/N-s for the top layer to 10 mm^3/N-s for the bottom layer (Chang and Zhang, 2010; Shi et al., 2015). The soil properties at several depths of the three dams refer to Chang and Zhang (2010). No geologic investigation was conducted on the two smaller dams. The two dams were assumed of the identical soil properties of the Tangjiashan landslide dam, and the soil properties were assumed to distribute proportionally to the dam height (Shi et al., 2015).

A spillway with a depth of 12 m, a bottom width of 8 m, and a top width of 44 m was constructed across the Tangjiashan landslide dam. The lake capacity was lowered from 316 to 247×10^6 m^3 (**Figure 4** and **Table 1**). No spillways had been constructed across the two dams downstream.

Figure 5 shows the simulated outflow rates after the cascading dam breaching of the three landslide dams as well as the records at the Tangjiashan hydrologic station and the Beichuan hydrologic station (Zhang, 2009; Shi et al., 2015). Note that the Tangjiashan station (just downstream of the Tangjiashan landslide dam) recorded the breaching outflow rate from the Tangjiashan landslide dam and the Beichuan Station (0.5 km downstream of the Xinjiecun landslide dam) approximately recorded the breaching outflow rate from the Xinjiecun landslide dam. The recorded peak discharge in Tangjiashan Station was 6500 m^3/s. The recorded discharge at Beichuan Station also had two peaks of 915 and 6540 m^3/s (**Table 2**), which were mainly caused by the breaching of the Kuzhuba and Tangjiashan landslide dams, respectively (Shi et al., 2015).

The Cascading Breaching Simulation
Validation of the DABA Model

The inputs for the modified DABA model are shown in **Table 1**. The K_d and τ_c values for the soils between any two depths (Chang and Zhang, 2010) were interpolated linearly. **Figure 5** shows outflow rates during the cascading breaching of the three dams. The detailed breaching parameters are shown in **Table 2**. The simulated peak outflow rate of the Tangjiashan landslide dam was 6603 m^3/s, which was close to the recorded value of 6500 m^3/s. The simulated peak outflow rate of the Xinjiecun landslide dam had three peaks of 1244, 418, and 6917 m^3/s, which were caused by the dam breaching of the Kuzhuba, Xinjiecun, and Tangjiashan landslide dams, respectively. It was pity that there were no records in the range around the simulated second peak outflow rate which was caused by the Xinjiecun landslide dam. Generally, the DABA model successfully captured the multi-peak outflow rate after cascading breaching of landslide dams in a series with relatively good simulated results.
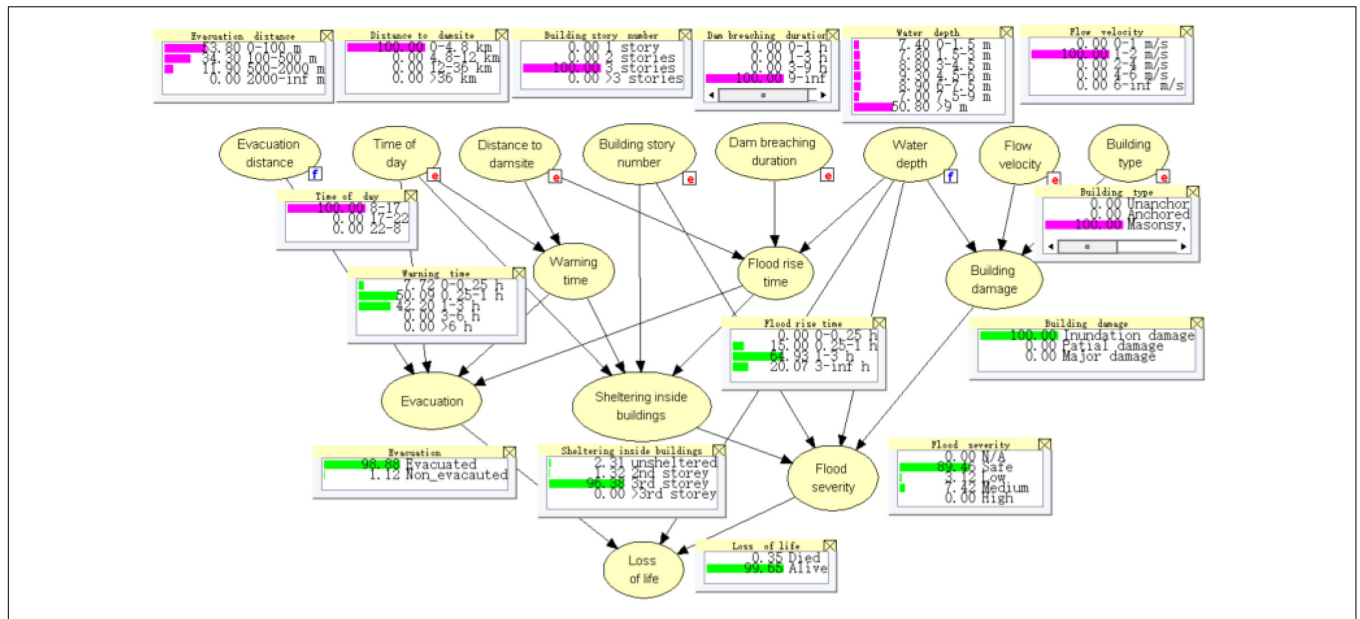
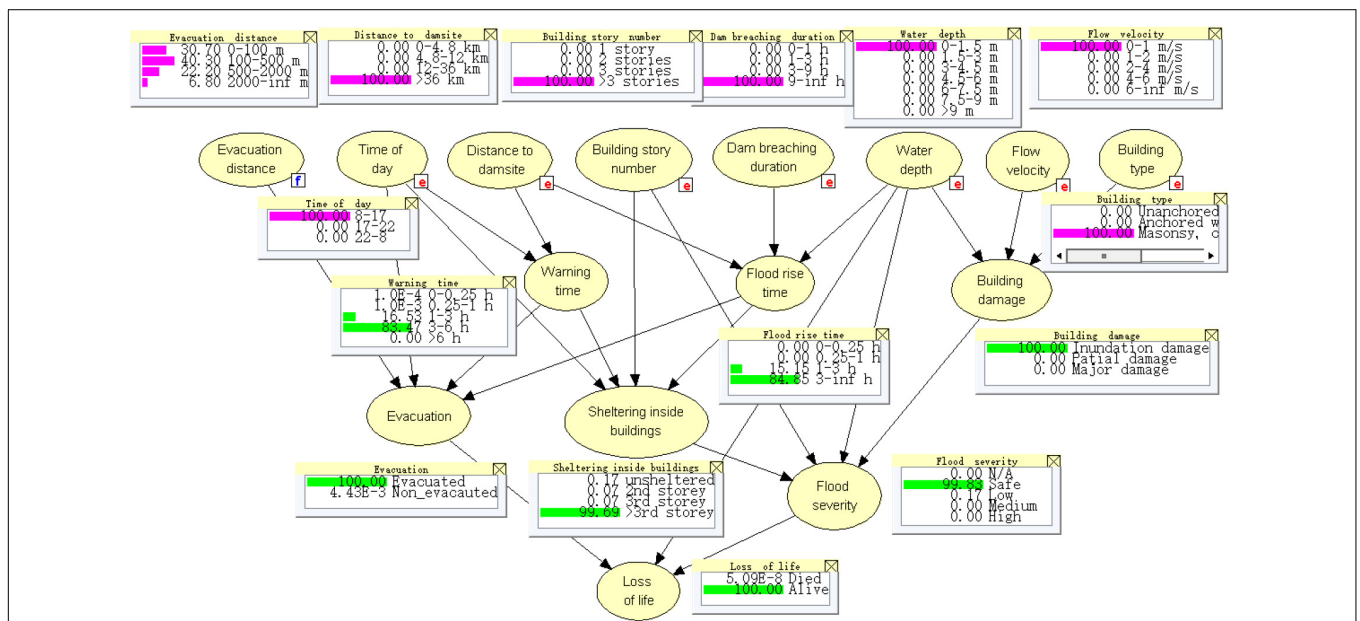**FIGURE 2 |** Risk assessment of Scenario 4 in Beichuan County.

FIGURE 3 | Risk assessment of Scenario 4 in Mianyang City.

Cascading Breaching Simulation

Shi et al. (2015) found the initial water level in a landslide lake did not influence the breaching process of a single dam but might significantly affect the cascading breaching outflow rate through overlapping effects. In this study, a virtual scenario was assumed with proper initial water levels to achieve the perfect overlapping flood (with maximal peak outflow rate). Besides, two more virtual scenarios were assumed without the constructed spillway to find out the influence of the constructed spillway: without and with the overlapping effect of cascading

dam breaching. In summary, four scenarios were considered as shown in **Table 2**.

In Scenario 1, the initial water levels in Tangjiashan, Kuzhuba, and Xinjiecun landslide dam lakes were set as the elevation of 740, 646, and 606 m, respectively, according to Shi et al. (2015). At that time, the water depths of the three landslide lakes were 70, 42, and 2 m, respectively. The Kuzhuba landslide dam first breached with a peak outflow rate of 1240 m^3/s. The breaching flood from the Kuzhuba landslide dam overtopped the Xinjiecun landslide dam but did not cause immediate failure
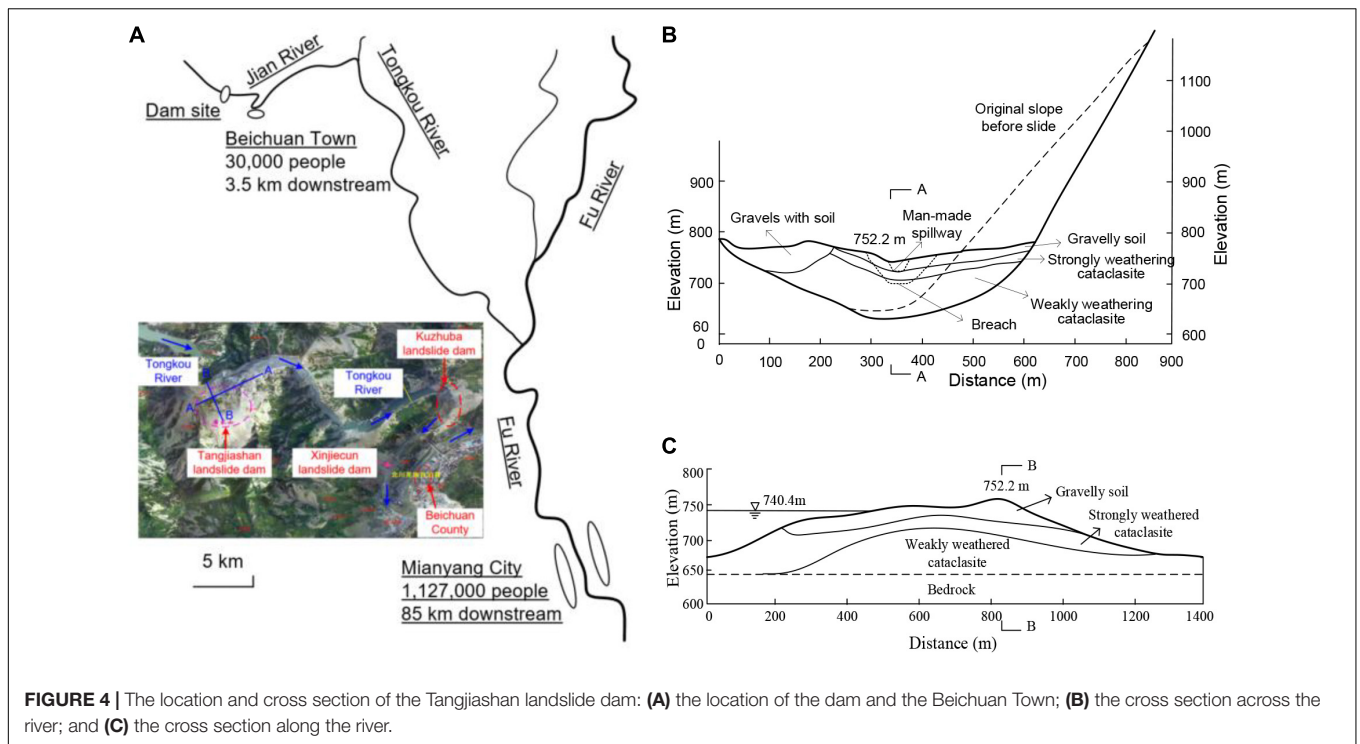
FIGURE 4 | The location and cross section of the Tangjiashan landslide dam: **(A)** the location of the dam and the Beichuan Town; **(B)** the cross section across the river; and **(C)** the cross section along the river.

of that dam. The latter breached 3 h after the Kuzhuba dam and formed the second peak of 418 m³/s. The Tangjiashan landslide dam breached 8 h later (with the peak outflow rate of 6603 m³/s) because of its long breach initial phase due to the large dam width of 350 m (Shi et al., 2015). In short,

TABLE 1 | Parameters of the three landslide dams (based on Shi et al., 2015).

Category	Parameters	Landslide dams		
		Tangjiashan	Kuzhuba	Xinjiecun
Dam and lake	Dam height (m)	82	60	20
	Dam crest width (m)	350	100	60
	Lake volume (×10⁶ m³)	316	18	2
	Upstream slope angle (degree)	20	20	20
	Downstream slope angle (degree)	13.5	28	13.5
	Longitudinal gradient of the dam crest	0.006	0.006	0.006
	Input initial water elevation (m)	740	646	582
Spillway	Spillway depth (m)	12	–	–
	Spillway bottom width (m)	8	–	–
	Side slope angle (degree)	33.7	–	–
	Spillway bottom elevation (m)	740	663	600
	Lake volume after spillway construction (×10⁶ m³)	224	18	2
	Critical slide slope angle, α_c (degree)	50	50	50
	Downstream critical slope angle, β_f (degree)	30	30	30

the three landslide dams were basically breached, respectively. The simulated breaching floods of the three landslide dams from upstream to downstream had one, two, and three peaks, respectively, as shown in **Table 2**.

In Scenario 2, when we simply set the initial water level of the Kuzhuba landslide lake from 646 to 606 m, the breaching start time was significantly delayed and perfectly met the coming of the Tangjiashan landslide dam breaching flood. The breaching flood of the Kuzhuba landslide dam was enlarged from 6,883 to 7,920 m³/s (**Table 2**). It seemed that the breaching floods of the two landslide dams overlapped. In this case, the peak outflow rate of the Xinjiecun landslide dam increased from 6,917 to 8,070 m³/s.

In Scenario 3 without the constructed spillway, the lake capacity of the Tangjiashan landslide dam would become 316 million m³ instead of 224 million m³ (**Table 1**). The breaching of the three dams would be delayed 38 h since more time was needed to fulfill the larger lake capacity. The breaching sequence of the three dams would not be changed. In this case, the peak outflow rate of the Tangjiashan landslide dam would become 13,688 m³/s. The peaks caused by the breaching of the Kuzhuba and Xinjiecun landslide dams would not be changed much since both of them breached before the coming of the peak discharge of the breaching flood upstream. Just like Scenario 1, the three landslide dams basically breached, respectively, forming two peaks downstream of the Kuzhuba landslide dam and three peaks downstream of the Xinjiecun landslide dam (**Table 2**).

In scenario 4, a larger overlapped peak outflow rate was achieved when we changed the initial water level of the Kuzhuba landslide lake from 646 to 629.2 m. In the case, the breaching start time of the Kuzhuba landslide dam would be
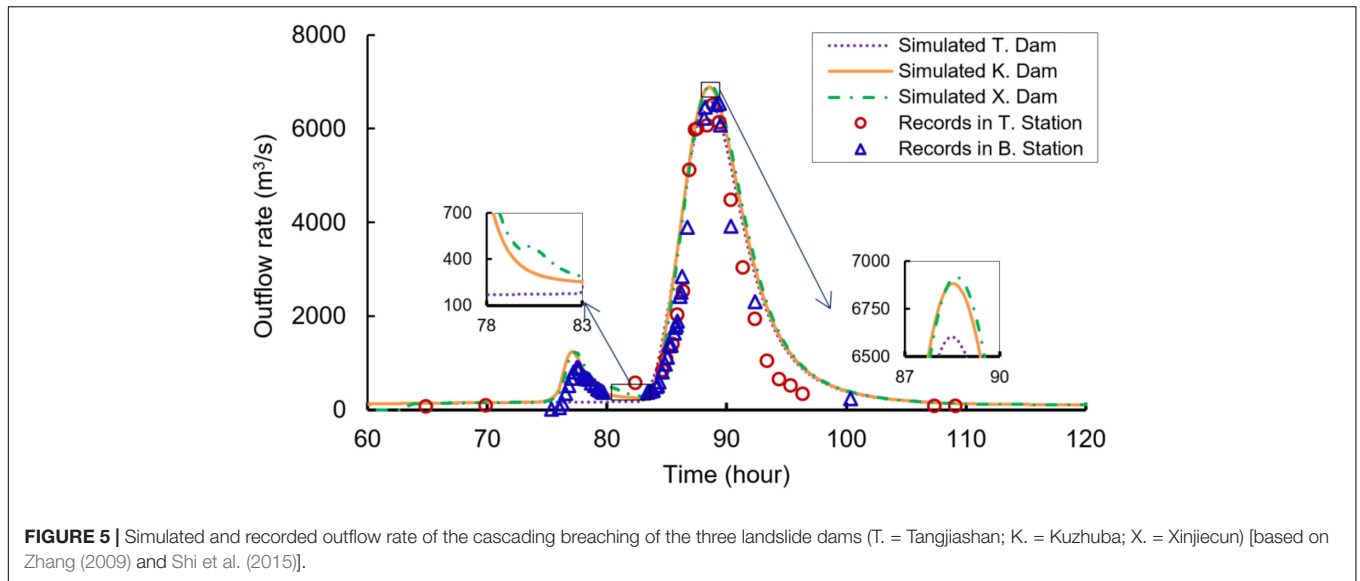
FIGURE 5 | Simulated and recorded outflow rate of the cascading breaching of the three landslide dams (T. = Tangjiashan; K. = Kuzhuba; X. = Xinjiecun) [based on Zhang (2009) and Shi et al. (2015)].

TABLE 2 | Peak outflow rates of the cascading breaching in four scenarios by considering the constructed spillway and the flood overlapping effect.

Scenario		Peak outflow rate (m³/s)					
		Tangjiashan	Kuzhuba		Xinjiecun		
			The 1st peak	The 2nd peak	The 1st peak	The 2nd peak	The 3rd peak
With spillway	Real case	6500	_[a]	_[a]	915	_[a]	6540
	1# Normal case	6603	1240	6883	1244	418	6917
	2# Overlapped case	6603	7920	_[b]	8070	_[b]	_[b]
Without spillway	3# Normal case	13688	1177	14236	1167	420	14299
	4# Overlapped case	13688	15083	_[b]	15279	_[b]	_[b]

[a] No records were available.
[b] There was only one peak outflow rate in the overlapped flood cases.

TABLE 3 | Hydraulic parameters of cascading breach in the four scenarios in Beichuan County.

Scenario		Peak outflow rate (m³/s)		River channel		Floodplain	
		Tangjiashan Dam site	Beichuan County	Water depth (m)	Flow velocity (m/s)	Water depth (m)	Flow velocity (m/s)
1	The 1st peak	6603	1244	7.54	3.03	1.34	0.24
	The 2nd peak	–	418	4.56	2.36	–	–
	The 3rd peak	–	6917	15.76	3.60	6.56	1.40
2	The peak*	6603	8070	16.36	3.66	7.16	1.50
3	The 1st peak	13688	1167	7.34	2.98	1.14	0.14
	The 2nd peak	–	420	4.57	2.37	–	–
	The 3rd peak	–	14299	20.46	3.91	13.26	1.73
4	The peak*	13688	15279	21.20	3.94	14.14	1.77

The meaning of "*" is to note that the overlapped case had only one peak outflow rate.

perfectly delayed and only one overlapped peak outflow rate of 15,279 m³/s occurred.

Flood Routing Simulation

HEC-RAS 4.1 was applied to simulate the flood routing within the range of 90 km downstream, including the Beichuan County (4.5 km downstream of the Tangjiashan dam site) and Mianyang city (85 km downstream of the Tangjiashan dam site). The geometry model of the Tangjiashan landslide dam and the river downstream based on HEC-RAS is shown in **Figure 6**. Thirty typical cross sections were captured from Google Map, and 5475 cross sections were interpolated between typical cross sections. The cross section of the landslide dam is shown at the upper right corner in **Figure 6**. A 12-m-depth spillway was set initially with
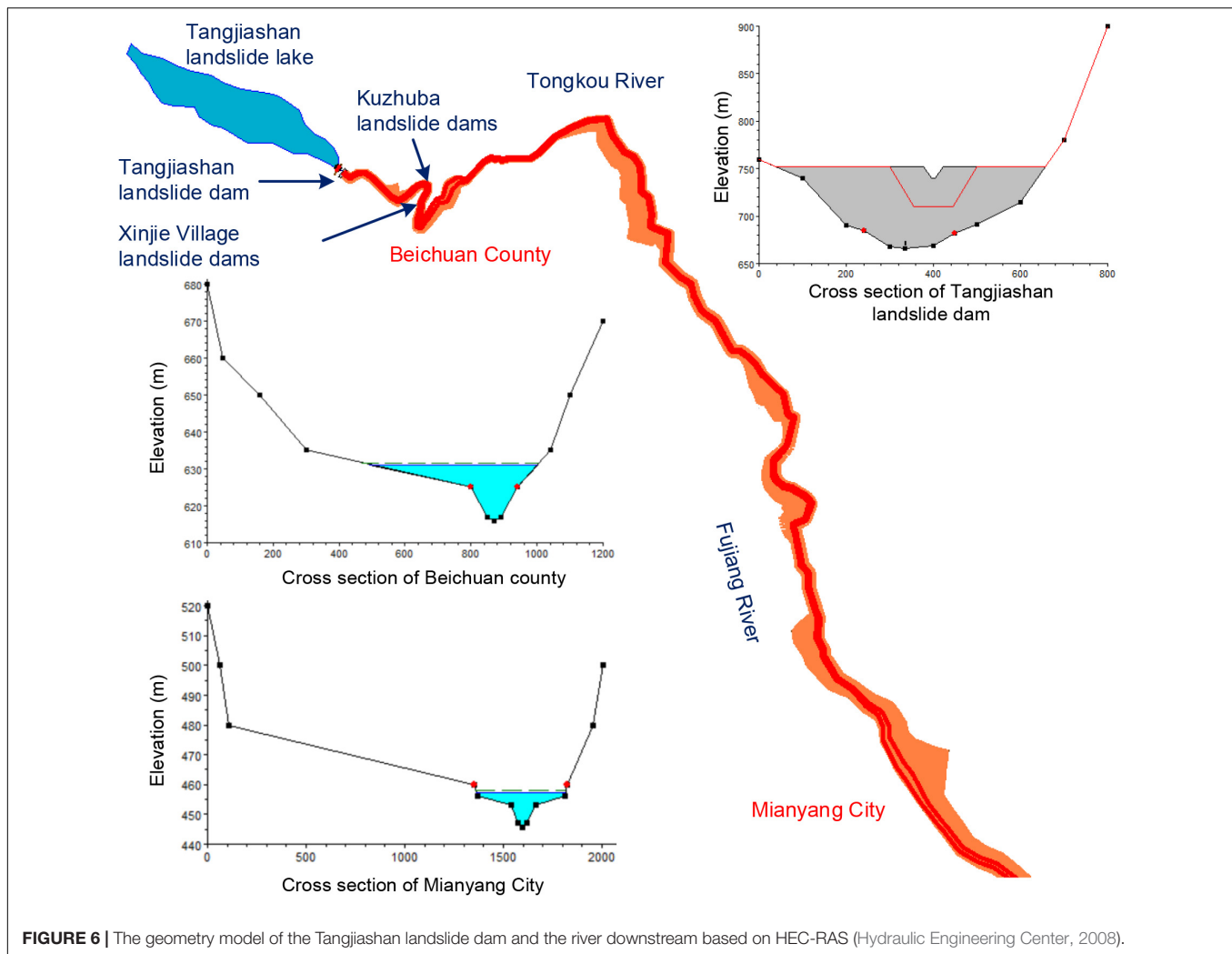
FIGURE 6 | The geometry model of the Tangjiashan landslide dam and the river downstream based on HEC-RAS (Hydraulic Engineering Center, 2008).

the elevation of 740 m. The final breach (red trapezoid), breach formation time, and breach progression were set according to the simulated results with DABA model. The Manning's *n* values of the channel and the floodplains were set as 0.04 and 0.05, respectively, according to Chow (1959).

The hydraulic parameter after the cascading dam breaching in Beichuan County is shown in **Table 3** and **Figure 7**. In Scenario 1, the 1st peak flood (1244 m^3/s) would flood Beichuan with the maximal water depth of 1.34 m and flow velocity of 0.24 m/s. The flooded area was 0.138 km^2, accounting for 15.1% of the whole residential area. The 2nd peak flood (418 m^3/s) is too small to result any flood in the county. However, the 3rd peak flood (6917 m^3/s) would incur much larger inundation with the maximal water level of 6.56 m and flow velocity of 1.40 m/s. The flooded area in this case would be 0.302 km^2, which accounted for 33.0% of the Beichuan County.

In Scenario 2, the overlapped flood with the peak outflow rate of 8070 m^3/s would flood the Beichuan County with the maximal water depth of 7.16 m and flow velocity of 1.50 m/s. The flooded area would increase to 0.325 km^2, which accounted for 35.5% of the Beichuan County.

In Scenario 3, the situations of the 1st and 2nd peaks were very similar to those of Scenario 1, since they were caused by the breaching of the Kuzhuba and Xinjiecun landslide dams, respectively. However, the 3rd peak flood (14299 m^3/s) inundated the Beichuan County with the maximal water depth as large as 13.26 m. The corresponding flooded area would be 0.509 km^2, accounting for 55.6% of the Beichuan County.
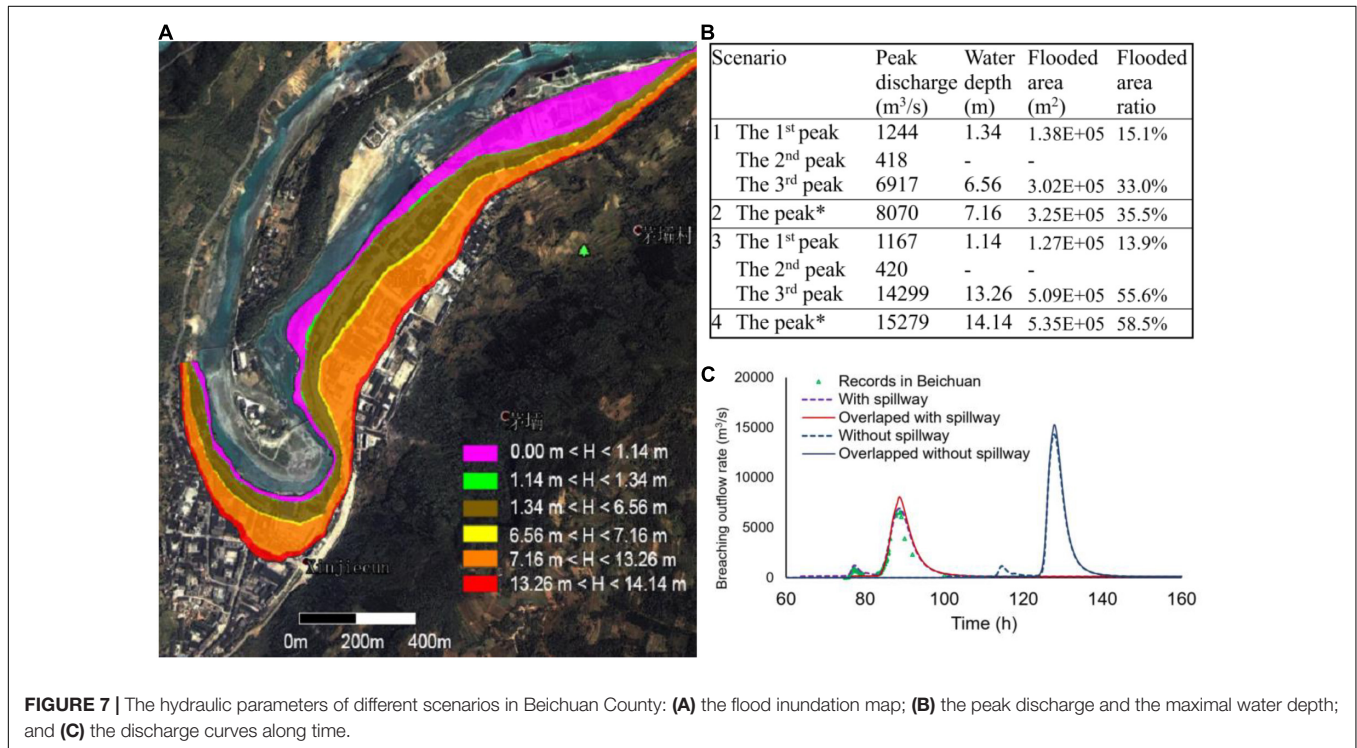
In Scenario 4, the overlapped flood with the peak outflow rate of 15,279 m^3/s flooded the Beichuan city with the maximal water depth of 14.14 m and flow velocity of 1.77 m/s. The inundated area would be 0.535 km^2, accounting for 58.5% of Beichuan County.

The hydraulic parameter after the cascading dam breaching in Mianyang City is shown in **Table 4** and **Figure 8**. Note, Mianyang is located on the bank of the Fujiang River, and Tongkou River is one of tributaries of the Fu River as shown in **Figure 4**. The peak discharges in the first two Scenarios were larger than those in Beichuan County due to the original discharge in Fujiang River. The peak discharge in Scenarios 1 and 2 (with spillway) were less than the designed flood of the Mianyang City with 12,000 m^3/s. The city would not be inundated in these two scenarios.

TABLE 4 | Hydraulic parameters of cascading breach in the four scenarios in Mianyang City.

Scenario		Peak outflow rate (m³/s)		River channel		Floodplain	
		Tangjiashan Dam site	Mianyang City	Water depth (m)	Flow velocity (m/s)	Water depth (m)	Flow velocity (m/s)
1	The 1st peak	6603	3063	8.61	3.23	–	–
	The 2nd peak	–	2357	5.94	3.11	–	–
	The 3rd peak	–	7910	12.38	3.54	–	–
2	The peak*	6603	8895	12.81	3.68	–	–
3	The 1st peak	13688	2997	8.56	3.20	–	–
	The 2nd peak	–	2359	5.95	3.12	–	–
	The 3rd peak	–	13206	15.16	4.69	0.66	0.44
4	The peak*	13688	14397	15.38	4.72	0.88	0.61

Only one peak occurred in Scenarios 2 and 4 due to overlapping effects. The meaning of "" is to note that the overlapped case had only one peak outflow rate.*

FIGURE 7 | The hydraulic parameters of different scenarios in Beichuan County: **(A)** the flood inundation map; **(B)** the peak discharge and the maximal water depth; and **(C)** the discharge curves along time.

In Scenarios 3 without the spillway in the Tangjiashan landslide dam, the peak discharge with 13,688 m³/s would inundate the Mianyang City with the maximal water depth of 0.66 m and the flow rate of 0.44 m/s. The flooded area would be 0.836 km², accounting for 1.43% of the whole city area. The maximal inundated water depth and flow rate in Scenario 4 were 0.88 m and 0.61 m/s, respectively. The corresponding flooded area would be 1.183 km², accounting for 1.96% of the whole-city area.

QUANTITATIVE RISK ASSESSMENT

Risk Assessment in Beichuan County

The populations in the urban area of both Beichuan County and Mianyang City were assumed uniformly distributed. The population at risk (P_{AR}) is defined as the number of the people in the inundated area without evacuation. P_{AR} can be calculated as:

$$P_{AR} = P_T \frac{A_F}{A_T} \tag{19}$$

where P_T is the total population in the studied area, A_F is the flooded area (in km²), and A_T is the total area in the studied area (in km²).

Scenario 4 is taken as an example to illustrate the risk assessment. Beichuan County was inundated of 58.5% area with P_{AR} of 17,552. As shown in **Figure 9**, the values of the upper eight root nodes (without parent nodes) in the Bayesian network are inputs based on the records and previously simulated results. The values of six root nodes were deterministic in the Beichuan: "Time of day" of the dam breaching was 7:00 am (in the range of 8–17), "Distance to the dam site" was 4.5 km (in the range
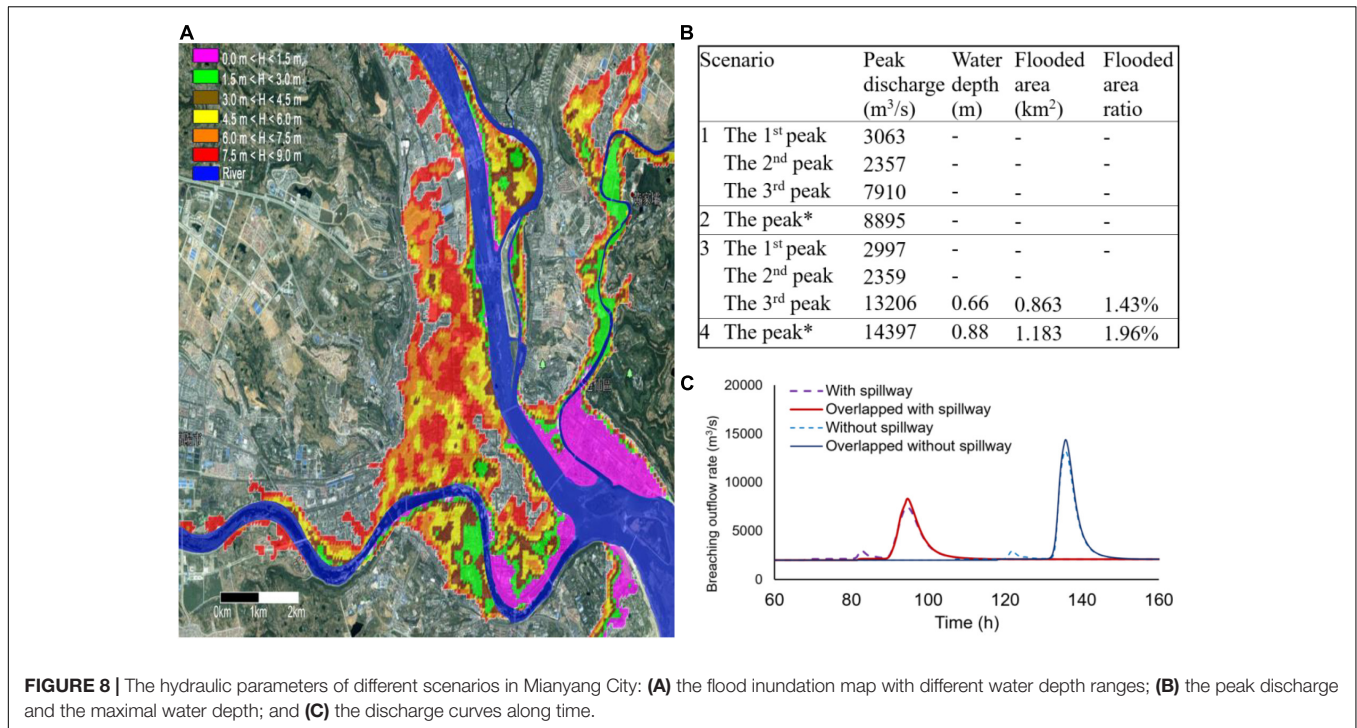
FIGURE 8 | The hydraulic parameters of different scenarios in Mianyang City: **(A)** the flood inundation map with different water depth ranges; **(B)** the peak discharge and the maximal water depth; and **(C)** the discharge curves along time.
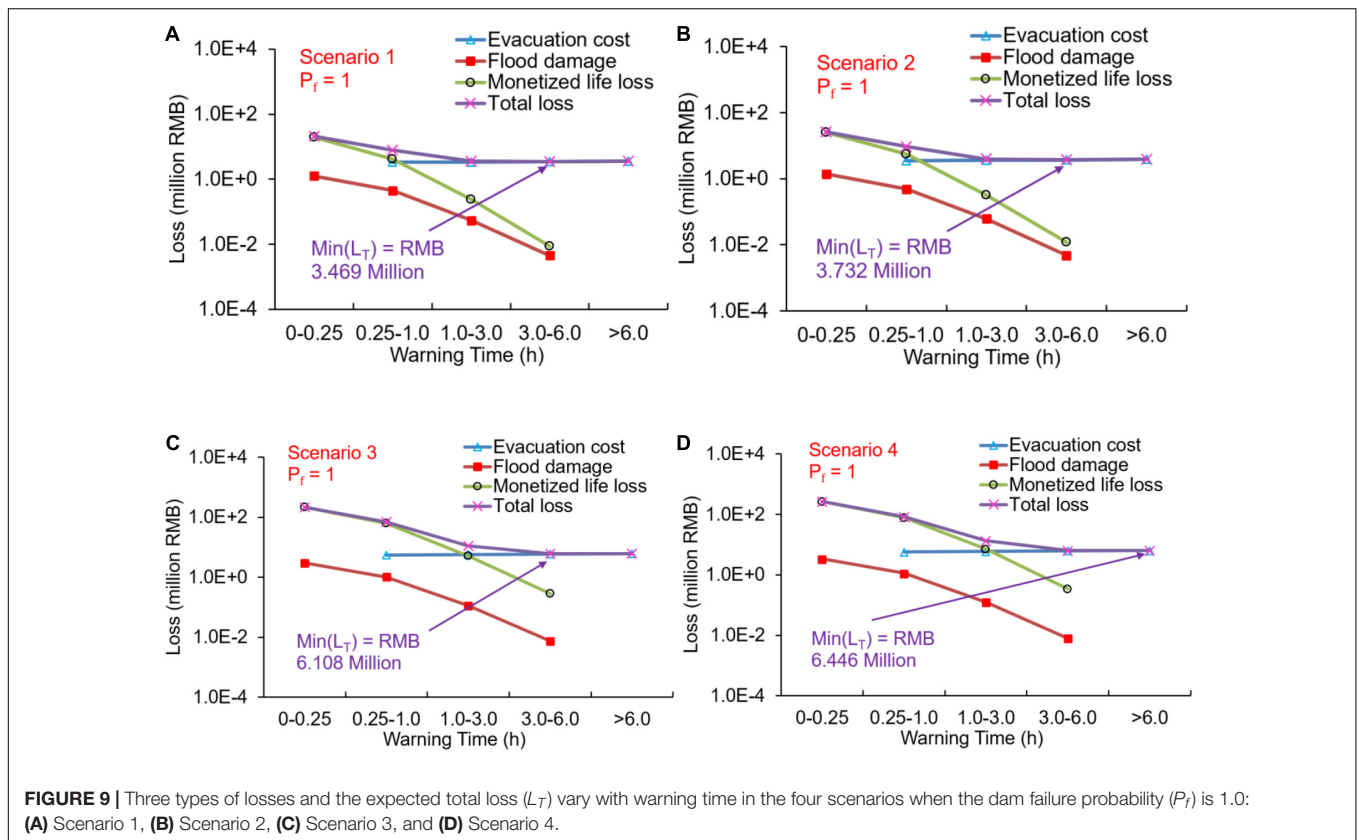

FIGURE 9 | Three types of losses and the expected total loss (L_T) vary with warning time in the four scenarios when the dam failure probability (P_f) is 1.0: **(A)** Scenario 1, **(B)** Scenario 2, **(C)** Scenario 3, and **(D)** Scenario 4.

of 0–4.8 km), "Building story number" was assumed as 3 stories on average, "Dam breaching duration" was 14 h (in the range of >9 h), the flow velocity was 1.77 m/s (in the range 1–2 m/s),

and "Building type" was Masonry, assuming that the people are uniformly distributed. The probabilities of the values of the other two root nodes, namely, "Evacuation distance" (P_{ed}) and "Water

depth" (P_{wd}), were determined based on the proportions of the corresponding area:

$$P_{ed} = \frac{A_{ed}}{A_F} \tag{20}$$

$$P_{wd} = \frac{A_{wd}}{A_F} \tag{21}$$

where A_{ed} is the area value (km^2) with the studied evacuation distance range (e.g., 0–100, 100–500, 500–2000, and >2000 m), and A_{wd} was the area value (km^2) with the studied water depth range (e.g., 0–1.5, 1.5–3.0, 3.0–4.5 m. . .). Both A_{ed} and A_{wd} were obtained based on flood routing simulation as shown in **Figure 7**.

According to Equation (20), the probabilities of people located in the areas with "Evacuation distances" of 0–100, 100–500, 500–2000, and >2000 m are 53.8, 34.3, 11.9%, and 0, respectively. Similarly, according to Equation (21), the probabilities of the people located in the areas with "Water depth" of 0–1.5, 1.5–3, 3–4.5, 4.5–6, 6–7.5, 7.5–9, and >9 m are 7.4, 7.8, 8.8, 9.3, 8.9, 7.0, and 50.8%, respectively.

The probabilities of evacuation and life loss can be achieved by updating the Bayesian network with these input values, according to Equations (6)–(8), as shown in **Figure 9**. The effective warning time concentrated in the range of 0.25–3 h, with the probabilities of 50.1 and 42.2% in the ranges of 0.25–1 h and 1–3 h, respectively. The evacuation rate was large (98.88%) because of the short evacuation distance (0–500 m) and relatively sufficient warning time. The probability of life loss was not very large (0.35%) due to the large evacuation rate.

The risk assessment results in all the four scenarios in Beichuan County were shown in **Table 5**. In Scenario 1, the first peak outflow rate of 1,244 m^3/s inundated 15.1% area of the Beichuan County with maximal water depth of 1.34 m and the population at risk of 4522. As many as 99.76% of the people managed to evacuate from the flooded area due to low

flood severity, short evacuation distance, and long warning time, making the fatality rate rather small (1.2E-7). The expected fatality number was 5.3E-4. The second peak outflow rate of 418 m^3/s did not incur any inundation in Beichuan. The third peak outflow rate of 6917 m^3/s inundated 33.0% area of the Beichuan County with maximal water depth of 6.56 m and population at risk of 9905. Risk assessment of the 3rd peak flood was a little bit complex. Three cases were considered according to different warning strategies, as shown in **Table 5**:

(1) Case 1 (Ind. case in **Table 5**) assumed that the warning in the 3rd peak flood was independent of that in the 1st peak flood, which means the warning in the 1st peak flood did not influence the warning in the 3rd peak flood. The evacuation rate (99.23%) was a little bit less than that of the 1st peak flood because of the larger flood area and longer evacuation distance. The fatality rate (3.6E-4) was much larger than that of the 1st peak flood due to the higher water depth. The expected fatality number is 3.6.

(2) Case 2 (War. case in **Table 5**) assumed that the warning in the 1st peak flood sufficiently warned the people in the 3rd peak flood. Since the 1st peak occurred 11 h earlier than the 3rd peak, all the people at risk managed to evacuate from the flooded area. No people were exposed and killed by the flood in this case.

(3) Case 3 (Bac. case in **Table 5**) assumed that people were misled by the 1st peak flood and believed that the dam breaching flood has gone. In this case, all the people went back home before the coming of the 3rd peak flood. The coming of the 3rd peak flood would make a sudden attack to the people in Beichuan County. The warning time was assumed as the least in the model of 0–0.25 h. The evacuation rate was 97.15%, and the fatality rate was 1.9E-3. The expected fatality number was as larger as 18.8.

In Scenario 2, the overlap effect made the unique peak outflow rate (8,070 m^3/s) larger than that in Scenario 1 (6,917 m^3/s).

TABLE 5 | Risk assessment results in Beichuan County.

Scenario				Population at risk	Evacuation rate%	Evacuated population	Fatality rate	Expected fatality number
No	Peak	Case	Q_p (m^3/s)					
1	1st	–	1244	4522	99.76	4511	1.2E-07	5.3E-4
	2nd	–	418	0	–	–	0	0
	3rd	Ind.	6917	9905	99.23	9829	3.6E-04	3.6
		War.	6917	9905	100	9905	0	0
		Bac.	6917	9905	97.15	9623	1.9E-03	18.8
2	1st	–	8070	10647	99.21	10563	4.0E-04	4.3
3	1st	–	1167	4174	99.76	4164	1.2E-07	4.9E-4
	2nd	–	420	0	–	–	0	0
	3rd	Ind.	14299	16682	98.95	16507	2.9E-03	48.4
		War.	14299	16682	100	16682	0	0
		Bac.	14299	16682	95.70	15965	1.47E-02	245.2
4	1st	–	15279	17552	98.88	17355	3.5E-03	61.4

Three cases are considered in the 3rd peak of Scenarios 1 and 3: Case 1 (Ind.) assumes that the warning in the 3rd peak flood is independent of that in the 1st peak flood; Case 2 (War.) assumes that the warning in the 1st peak flood also warns the people in the 3rd peak flood; and Case 3 (Bac.) assumes that people are misled by the 1st peak flood and believe the dam breaching flood has gone.

The larger inundation area ratio increased to 35.5%, and the population at risk increased to 10,647. Thanks to the large evacuation rate like that in Scenario 1, most people managed to evacuate. The fatality rate was 4.0E-4, and the expected fatality number was 4.3.

In Scenario 3, the risks of the 1st and 2nd peaks were quite similar to Scenario 1. The two peak outflow rates were caused by the breaching of the two downstream dams, which was not obviously influenced by the excavated division channel. The risk assessment in the 3rd peak was also divided into three cases. In Case 1, the larger peak outflow rate (14,299 m³/s) incurred more people at risk (16,682), larger fatality rate (2.9E-3), and more expected fatality number (48.4). In Case 2, no people were killed due to the longer warning time just like Scenario 1. In Case 3, the warning time was assumed as the least of 0–0.25 h, just like Scenario 1. In this case, the evacuation rate was 95.7%, the fatality rate was 1.47E-2, and the expected fatality number was as large as 245.2.

In Scenario 4, the overlap effect with large peak outflow rate (15,279 m³/s) would impact more people (17,552) and incur more fatality number (61.4) than those in Case 1 of Scenario 3. Despite of larger breaching flood, the expected fatality number of Scenario 4 was smaller than that of Case 3 in Scenario 3. The results show that the multi-peak flood could be more dangerous than the perfect overlapping-peak flood if no distinct warning order is issued to avoid misleading.

Risk Assessment in Mianyang City

Despite of the large number of residents (1.2 million), the breaching flood risk in Mianyang City was very low due to the long distance to dam site and low flood severity (low water depth and flow velocity). Taking Scenario 4 as an example (**Figure 10**), the long distance to the dam site (85 km) made the warning time much longer than that of the Beichuan County. The non-evacuation rate was as low as 4.43E-5. The low water depth (0.88 m) and the flow velocity (0.61 m/s) did not impact the buildings and people much, leading to low probability of life loss of 5.09E-8. The risk assessment results of all the four scenarios are shown in **Table 6**. The risks in Scenarios 1 and 2 are ignored since Mianyang City was not flooded. In Scenario 3, three cases are considered which are similar to those in Beichuan County. In Cases 1 and 2 (Ind. and War.), all people managed to evacuate from the flooded areas, leading to very low non-evacuation rates and fatality rates. In Case 3, the warning time was assumed as 0–0.25 h similar to Beichuan County. However, 99.68% people can be evacuated from the flooded area because of long flood rise time (the period between the arriving of the flood to the moment of the peak discharge, referring to Peng and Zhang, 2012b). The people were sufficiently warned by the flood itself. Among the 55 exposed people, all were able to take shelter on the top story of their buildings, which was much higher than the maximal water depth of 0.66 m. The fatality rate was very low with 1.42E-7. The risk to people can be basically ignored. In Scenario 4, despite
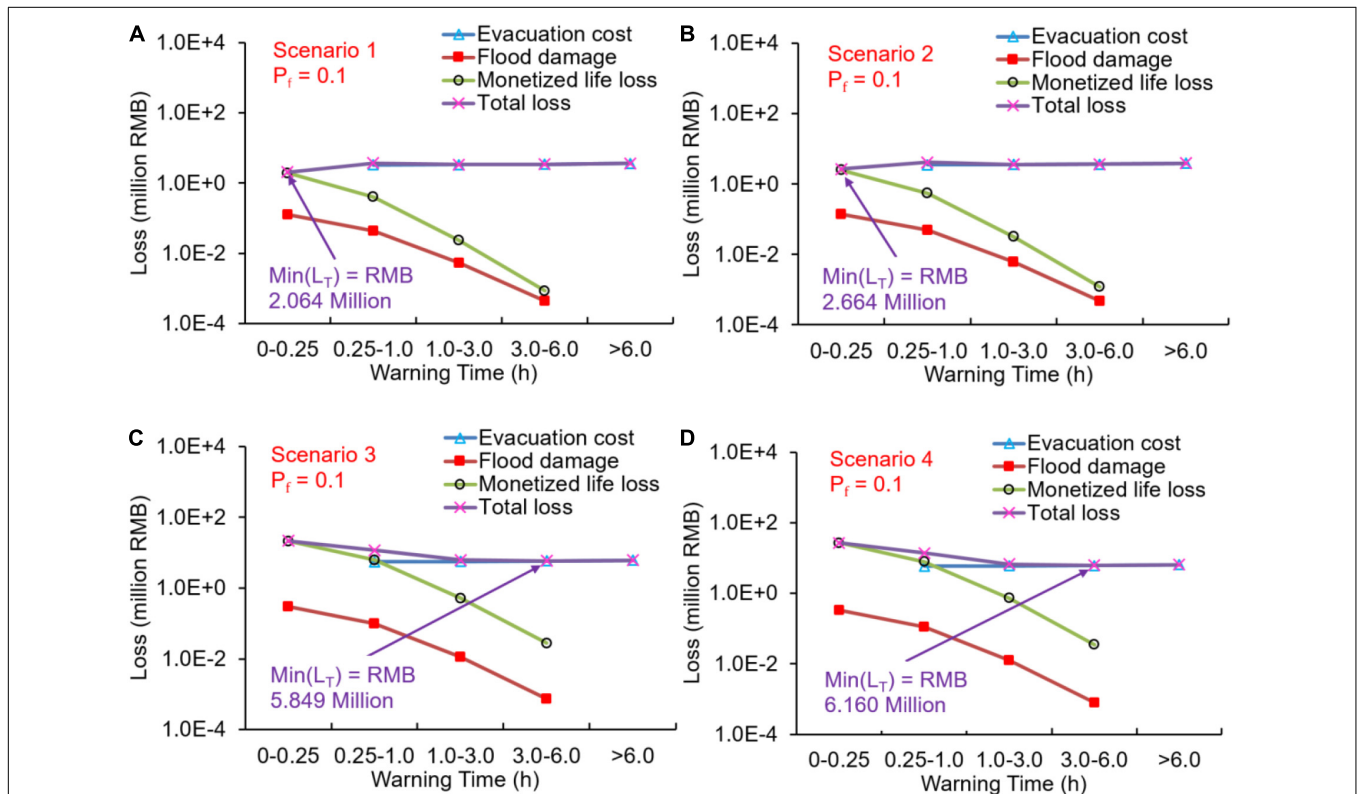

FIGURE 10 | Three types of losses and the expected total loss (L_T) vary with warning time in the four scenarios when the dam failure probability (P_f) is 0.1: **(A)** Scenario 1, **(B)** Scenario 2, **(C)** Scenario 3, and **(D)** Scenario 4.

TABLE 6 | Risk assessment results in Mianyang City.

Scenario				Population at risk	Non-evacuation rate	Evacuated population	Fatality rate	Expected fatality number
No	Peak	Case	Q_p (m^3/s)					
3	1st	–	2997	0	–	–	–	–
	2nd	–	2359	0	–	–	–	–
	3rd	Ind.	13206	17160	4.38E-5	17160	4.96E-10	8.51E-6
		War.	13206	17160	0	17160	0	0
		Bac.	13206	17160	0.32%	17105	1.42E-7	2.44E-4
4	1st	–	14397	23521	4.43E-5	23521	5.09E-10	1.20E-5

Mianyang City was not flooded in Scenarios 1 and 2.

of the more inundated area of 1.183 km^2 (**Figure 8**) and more people of 23521 (**Table 6**), the human risks were also very low due to long distance to dam site and low flood severity.

RISK-BASED WARNING DECISION MAKING

Deterministic Dam Failure

The time of dam failure was often assumed as the deterministic value for emergent decision making within a relatively short prediction lead time (e.g., several days before dam failure). In this case, the failure probability of the landslide dam is assumed as 1.0. The three types of losses in all the four scenarios are calculated and shown in **Table 7**.

In Scenario 1, only the 3rd peak flood was discussed here since the other two peak floods did not incur obvious human risk as discussed in Section 4. In Case 1 (Ind.), there is no evacuation cost since no warning was issued by governor and people were warned by the flood itself. D_M was 0.34 million RMB, and the M_L was 3.71 million RMB. The expected total loss was 4.05 million RMB, which was dominated by M_L due to insufficient warning. In Case 2 (War.), people are warned 11 h before the dam breaching. D_M and M_L were avoided, but C was larger with 3.72 million RMB. In Case 3 (Bac.), the misleading by the first discharge would cause high D_M (1.26 million RMB), M_L (19.4 million RMB), and L_T (20.6 million RMB). However, neither of the three cases was the optimal choice. The optimal warning decision would be achieved when issuing the warning 4.5 h before the dam breaching. In this case, a perfect balance was obtained between the evacuation cost and flood-cased loss, with L_T of 3.47 million RMB.

In Scenario 2, the optimal warning decision was also achieved with warning time of 4.5 h. L_T was RMB 3.73 million, which was only 65% of the loss when no warning was issued (RMB 5.73 million). L_T was slightly higher than that in Scenario 1 (RMB 3.47 million) due to higher peak discharge.

In Scenario 3, similar to Scenario 1, the expected total losses in the first two peak floods were ignored. In the 3rd peak floods, the L_Ts in the first three cases (i.e., the Ind. War. and Bac. cases) were RMB 50.6 million, 6.26 million, and 256 million, respectively. The larger breaching flood made more serious impact to human lives and properties. The optimal decision was to warn the people 4.5 h before the dam breaching, with the L_T of RMB 6.11 million.

In Scenario 4, the optimal warning decision can also be achieved with warning time of 9 h. L_T was RMB 6.45 million which accounted for only 10.1% of L_T when no warning was issued (RMB 64.1 million). L_T was slightly higher than that in Scenario 3 (RMB 6.11 million) due to relatively higher peak discharge.

No warning was needed in all the four scenarios in Mianyang City for the relatively low flood severity and long distance to the dam site.

Probabilistic Dam Failure

When the prediction lead time is relatively long (e.g., weeks to months), the time of dam failure is full of uncertainty. For instance, an unexpected heavy rainfall would highly increase the inflow rate of the landslide lake, substantially putting forward the dam failure. The dam failure probability is actually a time series with variation along time. In this section, the dam failure probability (P_f) is assumed as 1.0, 0.1, and 0.01 to investigate the influence of the failure probability on the optimal warning decision.

Figure 11 shows the three types of losses and the expected total loss (L_T) varying with warning time with a dam failure probability (P_f) of 1.0 in the four scenarios. The optimal decision of Scenario 1 was to warn the people 3.0–6.0 h before the predicted dam failure time, with the minimal L_T of RMB 3.469 million. In Scenario 2 with slight larger breaching flood, the optimal decision strategy did not change with a slight larger minimal L_T of RMB 3.732 million. In Scenario 3, the optimal warning was also 3.0–6.0 h with the minimal L_T of RMB 6.108 for much larger flood severity. In Scenario 4, the increase of the flood risk should be properly reduced by more warning time of >6.0 h, with slightly larger minimal L_T of RMB 6.446.

When the dam failure probability became 0.1, the expected flood damage and the monetized life loss decreased by an order of magnitude. In Scenarios 1, the minimal L_T was achieved as RMB 2.064 million, when warning time was the least (0–0.25 h). Note that the evacuation cost was assumed as 0 when warning time was 0–0.25 h. L_T increased steadily with warning time as it was gradually dominated by evacuation cost. The influence of the flood damage and monetized life loss can be ignored when warning time was larger than 1 h. The decision strategy in Scenario 2 was similar to that in Scenario 1. No warning was needed for low dam failure probability with min(L_T) of RMB

TABLE 7 | Risk-based warning decision making in Beichuan County under deterministic dam breaching time.

Scenario		Warning time (h)	C^a (RMB)	$D_M{}^a$ (RMB)	$M_L{}^a$ (RMB)	$L_T{}^a$ (RMB)
No.	Case					
1^b	Ind.	–	0	3.41E05	3.71E06	4.05E06
	War.	11	3.72E06	0	0	3.72E06
	Bac.	–	0	1.26E06	1.94E07	2.06E07
	Optimal warning	4.5^c	3.46E06	4.44E03	8.61E03	3.47E06
2	No warning	–	0	3.36E05	4.39E06	4.73E06
	Optimal warning	4.5^c	7.72E06	4.77E03	1.22E04	3.73E06
3^b	Ind.	–	0	7.01E05	4.99E07	5.06E07
	War.	11	6.26E06	0	0	6.26E06
	Bac.	–	0	3.00E06	2.13E08	2.16E08
	Optimal warning	4.5^c	5.82E06	7.47E03	2.80E05	6.11E06
4	No warning	–	0	7.86E05	6.33E07	6.41E07
	Optimal warning	9^c	6.45E06	0	0	6.45E06

$^a C$ denotes evacuation cost; D_M denotes moveable flood damage; M_L denotes the monetized life loss; and L_T denotes the expected total loss.
^{b} Only the 3rd peak flood is considered since the first two peak floods did not incur much loss.
^{c} The warning times were set as the average value of 4.5 and 9 h for calculating the evacuation costs in the ranges of 3–6 and >6 h in the Bayesian network, respectively.
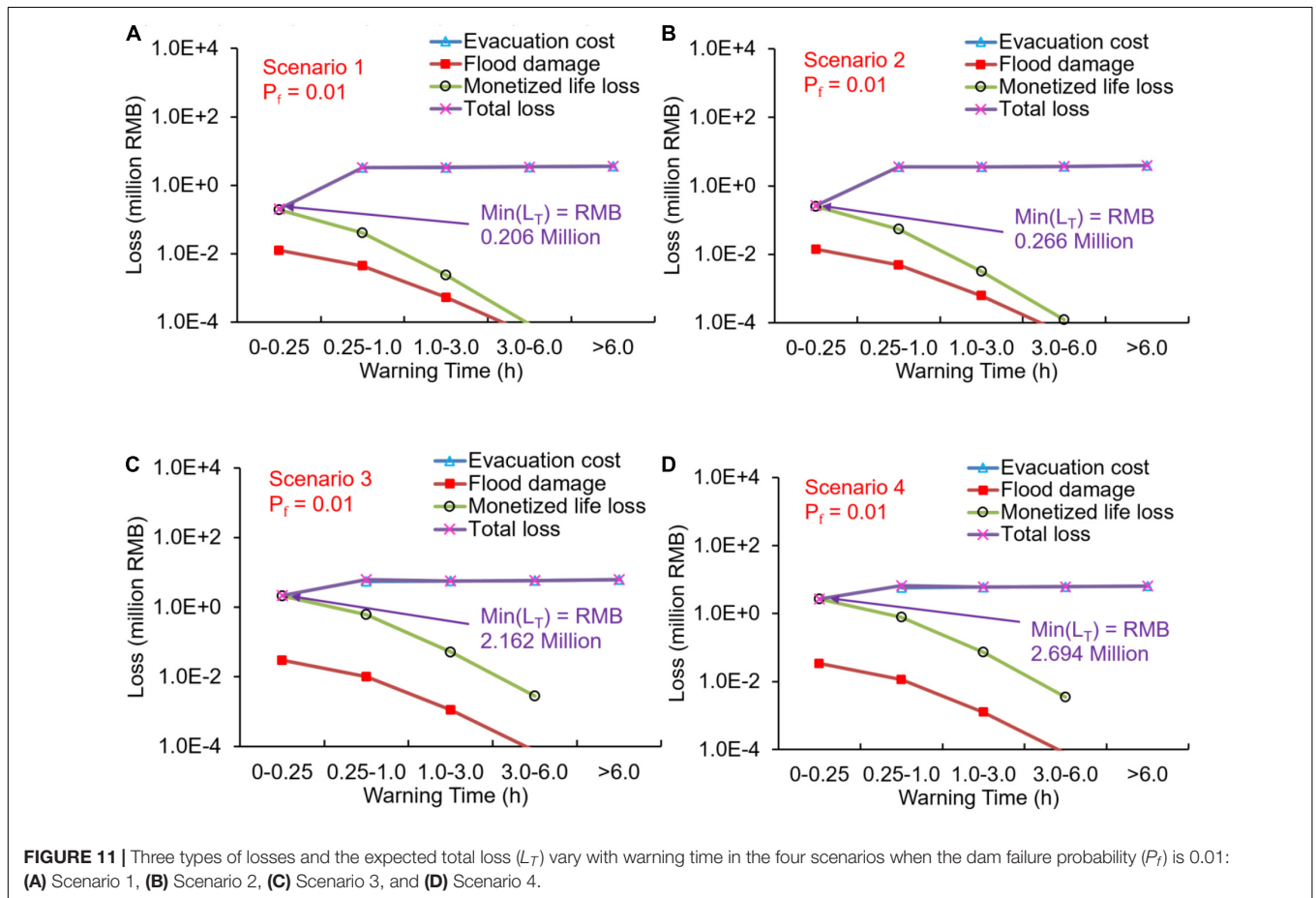

FIGURE 11 | Three types of losses and the expected total loss (L_T) vary with warning time in the four scenarios when the dam failure probability (P_f) is 0.01: **(A)** Scenario 1, **(B)** Scenario 2, **(C)** Scenario 3, and **(D)** Scenario 4.

2.664 million. However, in Scenario 3 with larger flood severity, the warning time of 3.0–6.0 h was recommended with min(L_T) of RMB 5.849 million, which indicated that a small probability could also be dangerous if the potential loss is extremely large.

min(L_T) increased to RMB 5.849 million in Scenario 4 with slightly larger flood severity.

When the dam failure probability decreased to 0.01, no warning was preferred in all the four scenarios since L_T

monotonically increased with warning time. The minimal L_T in the Scenarios 1 to 4 were RMB 0.206, 0.266, 2.162, and 2.694 million, respectively.

Generally, P_f proportionally influences the life loss and flood damage but does not influence the evacuation cost. L_T significantly decrease with P_f when the warning time was insufficient. However, L_T would not change much when warning time is sufficient, since the life loss and flood damage do not matter any more.

DISCUSSION

Cascading Dam Breaching

The cascading breaching of landslide dams strongly depends on the time-related hydraulics in both upstream and downstream landslide dams. When the upstream dam is much smaller than the downstream dam, the dam breaching of the upstream dam would not obviously influence the breaching of the downstream dam, as the larger lake capacity downstream would be able to keep inside all the breaching flood of the upstream dam. This case will not be discussed later on.

When the upstream landslide dam is much larger, the downstream dam is likely to breach firstly (e.g., the Tangjiashan and Kuzhuba dams in this study). The reason is that the breaching initiation phase (i.e., the phase between the start of the overflow and the moment when the erosion achieves the upstream slope, referring to Peng et al., 2014) is often very long due to the large dam crest and flat downstream slope. The lasting overflow through the upstream dam and the confluence flows from tributaries between the two dams are very like to fulfill the downstream lake and trigger the dam breach. In this case, the cascade dam breach forms a multi-peak flood.

When the two landslide dams are in similar sizes (e.g., the 2008 Xiaogangjian and Yibadao landslide dams triggered by the Ms 7.9 Wenchuan earthquake, referring to Peng et al., 2014), the breaching flood of the upstream dam is very likely to pass across the crest of the downstream dam before the dam development phase (Peng et al., 2014), forming multi-peak flood. In short, cascading breaching of a series of landslide dams is more likely to form a multi-peak flood downstream other than an overlapped-peak flood.

In some extremely cases when the coming of the breaching flood from the upstream dam overlaps with the dam breaching flood of the downstream dam, a higher overlapped-peak flood may occur. However, the overlapped-peak outflow rate would not be much larger than the sum of the peak outflow rates of the single dam breaching of the two landslide dams. For instance, the perfectly overlapped-peak outflow rate (the maximal overlapped-peak outflow rate with perfect match) of the Tangjiashan and Kuzhuba landslide dam was 7920 m³/s, which was only slightly larger than the sum of the peak outflow rates of the single dam breaching of two landslide dams (6603 + 1240 = 7843 m³/s). The reason is that the large inflow rate from the upstream dam breaching would not incur collapse of the downstream dam because of the rather flat slopes. Both of the upstream and downstream slopes of a landslide dam are flat due to the rapid and dynamic deposition of landslides during the formation of the landslide dam. Besides, the amount of the erosion during the short period around the moment of the peak discharge of the inflow is limited. Thus, a sharp amplification of the peak discharge is not possible for cascade breaching of landslide dams.

Risk Assessment and Warning Decision Making

The cascading breaching of landslide dams, which incurs overlapped-peak flood or multi-peak flood, bring different risks to the downstream area to those of single dam breach.

When overlapped-peak flood occurs, the flood risk would be larger than the dam breaching of a single dam. A larger area with more people and properties would be impacted. The life loss and flood damage would be much higher under larger flood severity. In this case, evacuation warning needs to be issued earlier to avoid serious life loss and flood damages but would pay more evacuation costs at the same time. The $Min(L_T)$ under optimal decision would be larger than that of the dam breaching a single dam. For instance, in Beichuan County as shown in **Table 7**, the $Min(L_T)$ was RMB 3.73 million in Scenario 2, which was larger than that in Scenario 1 (RMB 3.47 million). Similarly, the $Min(L_T)$ was RMB 6.45 million in Scenario 4, which was larger than that in Scenario 3 (RMB 6.41 million).

When multi-peak flood occurs, the former peak flood (normally with smaller peak discharge) would highly influence the risks of the peak flood thereafter (normally with larger peak discharge). If the duration between the two peaks is short, people who have been warned by the former peak flood would avoid the impact from the peak flood thereafter. However, if the duration between the two peaks is relatively long, people may believe that the dam-breaching flood has gone after the previous peak flood. They may go back home in a hurry to check the flood damage and rescue properties. The surprise attack of the peak flood thereafter may incur catastrophic loss to the returned people, which may be even higher than that of the overlapped-peak flood situation. Case 3 (Bac. case) in Scenarios 1 and 3 belongs to this case. The expected fatality number (**Table 5**) was 18.8 in Case 3 of Scenario 1, which is much larger than the single dam breaching case (3.0 in Case 1 of Scenario 1) and even larger than the overlapped-peak flood (4.3 in Scenario 2). Similarly, the expected fatality number (**Table 5**) was 245.2 in Case 3 of Scenario 4, which is much larger than the single dam breaching case (48.4 in Case 1 of Scenario 3) and even larger than the overlapped-peak flood 61.4 in Scenario 4).

In the multi-peak flood case, systematical decision making should be conducted to sufficiently concern the risk caused by each peak of the breaching flood. Emphasis should be put on the influence of the former warning on the warning effect of the warning thereafter. The people to-be-evacuated should be clearly noticed with the information of multi-peak flood to strictly avoid misleading by the previous peak flood.

CONCLUSION

The paper conducted quantitatively risk-based decision making for the Tangjiashan landslide dams and two small downstream dams in four scenarios: the real case with the constructed

spillway, a virtual case without the spillway, and two more virtual cases with amplified floods by considering the overlapping effect on the basis of the first two scenarios. The following conclusions can be drawn:

(1) Cascade breaching of a series of landslide dams which is properly simulated with the DABA model is more likely to produce a multi-peak flood. A higher overlapped peak flood would occur when the coming of the breaching flood from the upstream dam perfectly overlaps with the dam breaching flood of the downstream dam. The overlapped-peak outflow rate would not be much larger than the sum of the peak outflow rates of the single dam breaching of the two landslide dams.

(2) When overlapped-peak flood occurs, the flood risk of cascading dam breaching would be larger than the dam breaching of any of the landslide dams. When multi-peak flood occurs, the warning for the former peak flood would also warn the peak flood thereafter if the duration between the two peaks is relatively short. However, people may be misled by the warning of the previous peak flood which is relatively long and suffer catastrophic flood impact.

(3) The optimal warning decision of cascading dam breaching can be achieved by minimizing the expected total loss. In the overlapped-peak flood case, evacuation warning needs to be issued earlier to avoid serious life loss and flood damages. In the multi-peak flood case, systematical decision making should be conducted to sufficiently concern the risk caused by each peak of the breaching flood. Emphasis should be put on the influence of the former peak flood on the risks of the peak flood thereafter.

(4) The dam failure probability P_f linearly influences the expected life loss and flood damage and does not influence the evacuation cost. The expected total loss significantly decreases with P_f when the warning time was insufficient. However, it would not change much with P_f when warning time is sufficient.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the manuscript/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

YZ performed writing original draft, calculation, and analysis. MP performed conceptualization, supervision, methodology, and funding acquisition. SC performed writing original draft and funding acquisition. LZ performed conceptualization, resources, writing, review and editing. All authors contributed to the article and approved the submitted version.

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