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Assessment and Simulation of Glacier Lake Outburst Floods for Longbasaba and Pida Lakes, China

Longbasaba and Pida lakes are two moraine-dammed lakes located at the headwaters of the Geiqu River, a tributary of the Pumqu River in the Chinese Himalayas, at an elevation of about 5700 m. The minimum distance between the two lakes is 24 m and their difference in elevation is about 76 m. Breach risks were assessed on the basis of field surveys carried out in the summers of 2004, 2005, and 2006. Empirical formulae for breaching of moraine dams and the BREACH model for earthen dam failure were employed to simulate the breach properties and hydrograph of floods at the breaching site of the dam from the two lakes. The modeling showed that an outburst flood from Longbasaba and Pida lakes would last for about 5.5 hours and have a peak discharge of about 3–5 × 10^4 m^3/s at about 1.8 hours after the beginning of the outburst.

Keywords: *Moraine-dammed lake; Pumqu River Basin; GLOF; assessment and simulation; Himalayas; China.*

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Introduction

Glacier lake outburst floods (GLOFs) are increasingly threatening people and property and are studied intensively worldwide. Research on GLOFs mainly involves assessments and simulations (Wang and Liu 2007). As early as 1953, scientists in Peru developed an important index to determine a lake's stability (Carey 2005). After that, qualitative assessment indexes were provided based on the topographic setting and the mother glacier's lake characteristics (Liu and Sharma 1988; Yamada 1993); recently, semi-quantitative and quantitative breach risk assessment methods were used to determine the probability of a moraine-dammed lake failure based on the characteristics of breached lakes (Lu et al 1999; Walder et al 2003; Huggel et al 2004; Hubbard et al 2005; McKillop and Clague 2007a).

Besides these risk assessment methods, both empirical formulae and physically based process models were established to obtain moraine-dammed lake breaching properties. The empirical formulae mainly included the relations between lake depth and area, lake volume and area, peak discharge (Q_{max}), and lake volume or potential energy (Evans 1986; Costa and Schuster 1988; Walder and O'Connor 1997; Cenderelli and Wohl 2001; Huggel et al 2002, 2004; McKillop and Clague 2007b). Physically based process models, such as DAMBRK, BREACH, and SOBEK, were also applied in the glacier lakes breach simulations (WECS 1987; Carrivick 2006; Bajracharya et al 2007). In recent years, the integration of remote sensing data with a GIS model has become an increasingly important means of simulating GLOFs (Huggel et al 2003; Carrivick 2006).

The present article first assesses the breach risks of two moraine-dammed lakes, Longbasaba and Pida lakes in the Chinese Himalayas. Then empirical formulae and the BREACH model are employed to simulate the outburst flood hydrograph at the breaching site of Longbasaba Lake, and the reliabilities of assessment and simulation results are discussed.

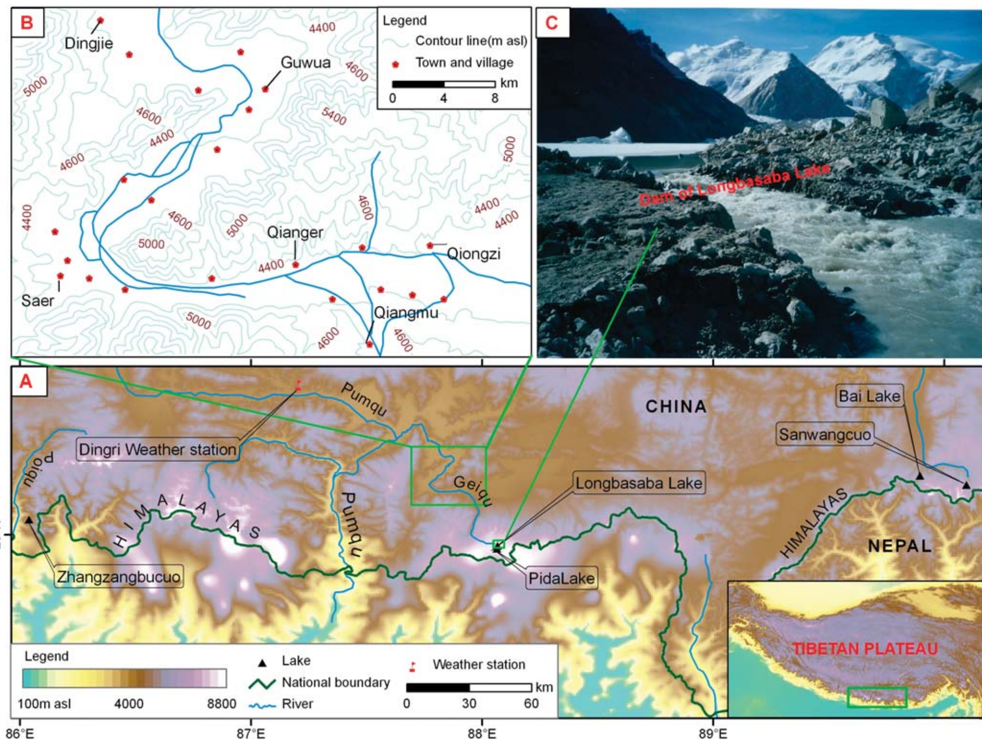
Study area and problems

Longbasaba and Pida lakes are two moraine-dammed lakes at an altitude of about 5700 m, located at the headwaters of the Geiqu River, which is a tributary of the Pumqu in the Himalayas of China at latitude 27°56.67′N and longitude 88°04.21′E (Figure 1A). Longbasaba Lake has an area of 1.08 km^2 and Pida Lake an area of 0.97 km^2; both lakes had an average depth of 52 m in 2005. The minimum distance between the two lakes is 24 m, and the outflow of Pida Lake seeps directly into Longbasaba Lake, as the altitude of the former is 76 m higher than that of the latter.

Nearby villages first reported that Longbasaba and Pida lakes were in danger of failure in 2002. On the one hand, data from the Dingri Weather Station (Figure 1A) show that temperature increased at the rate of nearly 0.04°C a^{-1} from 1960 to 2004 in this region. Owing to climate warming, the areas of the Longbasaba and Kaer glaciers (the "mother glaciers" of the two lakes), which terminate in Longbasaba Lake for the first and Pida Lake for the second, decreased by 8.7% and 16.6%, respectively, from 1978 to 2005, while the areas of Longbasaba and Pida lakes increased by 140% and 194%, and retreat of the mother glaciers led directly to growth of the two lakes, as shown in Figure 2. On the other hand, if a GLOF had occurred at the two lakes, 23 towns and villages would have been endangered (Figure 1B), including more than 12,500 people in China, according to the Hazard Investigation Report on Longbasaba and Pida lakes issued by the Hydrological Department of the Tibet Autonomous Region in 2006. Therefore, the status of Longbasaba and Pida lakes is intensely monitored by the Chinese government and the villages in the vicinity.

Methods and materials

Three types of survey were carried out for this study. First, field surveys were done to examine the area,



FIGURES 1A–C A) Location map of the study areas in the Chinese Himalayas (digital elevations are derived from Shuttle Radar Topography Mission (SRTM) data); B) villages and towns most likely to be affected by the outburst flood (contours in meters, adapted from Chinese topographic maps at 1:50,000); C) Longbasaba Lake and its natural dam. (Maps by authors; Photo by J. Ma, Greenpeace)

depth, moraine dams, mother glaciers, and drainage systems of Longbasaba and Pida lakes in the summers of 2004, 2005, and 2006. Second, samples of dam materials were taken to obtain the attribute parameters of unit weight, internal friction angle (by consolidated-drained triaxial compression test), and grain size of 50% finer (by sieve analysis) for the dams, in the State Key Laboratory of Cryosphere Science, Cold and Arid Regions Environmental and Engineering Research Institute. The cohesive strength was assumed to be zero, since the sample moraine was unconsolidated (Zhang and Liu 1994; Bajracharya et al 2007). Third, some documents, such as a topographic map at the scale of 1:50,000, TM images from 1989 and 2000, a 2005 ASTER image, and meteorological data for 1960–2004, were also collected.

The present article employs empirical formulae for breaching of moraine dams (Table 2) and the BREACH model for earthen dam failure to simulate the hydrograph of floods at the breach site of the two lakes. The empirical formulae are based either on the lake volume or on the potential energy of lake water, PE, which is the product of dam height, lake volume, and the specific weight of water. All the selected empirical formulae could be used for the moraine-dammed lakes.

A physically based mathematical model for earthen dam failures, the BREACH model, was developed by coupling the conservation of mass of the reservoir inflow, spillway outflow, and breach outflow with the sediment transport capacity of the unsteady uniform

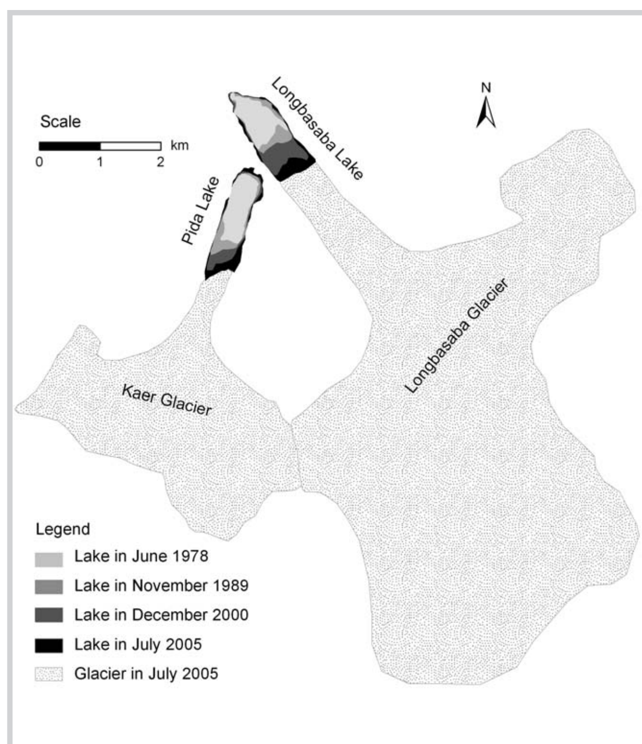


FIGURE 2 Growth of Pida and Longbasaba lakes and retreat of Kaer and Longbasaba glaciers from 1978 to 2005; based on a 1978 air photo, TM images from 1989 and 2000, and a 2005 ASTER image.

TABLE 1 Indicators to evaluate the breaching risk of Longbasaba and Pida lakes.

Assessment object	Variable/indicator	Value of most likely breaching	Reference	Rating for the 2 lakes' breaching risk	Data source
Stability of moraine dam	Top width of dam (m)	< 600	*Lu et al 1999*	< 163 / high	Field survey
	Distal flank steepness (°)	> 20	*Lu et al 1999*	22 / high	Field survey
	Ice-cored / ice-free areas of moraine	Ice core	*Richardson and Reynolds 2000*	Ice core exposure somewhere in dams / high	Field survey
	Ratio of dam width to height	0.1–02	*Huggel et al 2004*	0.16 / high	Field survey
State of mother glacier (from which the lakes formed)	Glacier area (km^2)		*Lu et al 1999*	39.2 / high	ASTER in 2005
	Slope of glacier snout (°)	> 8	*Lu et al 1999*	10 / high	Topographic map 1:50,000
Climatic setting	Temperature and precipitation	Combination of high temperature–wetness or high temperature–dryness	*Lu et al 1999; Huggel et al 2004*	Temperature rising rate is 0.04°C a^{-1} during 1960s–2004 / high	From Dingjie meteorological station
Lake water level and dam height relation	Ratio of freeboard to dam height	0	*WECS 1987*	0 in overtop flowing / high	Field survey
Lake and mother glacier relation	Lake–glacier proximity (m)	< 500	*Lu et al 1999*	0 / high	Field survey

flow along an erosion-formed breached channel (Fread 1991). The model uses equations of weir or orifice flow to simulate the outflow entering a channel that is gradually eroded through an earthen dam. Conservation of reservoir inflow, storage volume, and outflow determines the time-dependent reservoir water elevation which, along with the predicted breach bottom elevation, determines the head controlling the reservoir outflow. Breach enlargement is governed by the rate of erosion, which is a function of the breach bottom slope and depth of flow, and by the extent of collapse that occurs at the sides of the breach due to one or more sequential slope failures. Though the BREACH model was initially designed for an earthen dam, it has also been used extensively to predict the breaching properties of moraine-dammed lakes in the Himalayas (WECS 1987; Zhang and Liu 1994; Bajracharya et al 2007).

Modeling and results

Breaching risk assessment

We managed to assess the breaching risk (ie evaluate the probability of dam failure) of Longbasaba and Pida lakes by field survey evaluation and through breaching risk assessment indexes. The field survey showed that the two lakes are at a high risk of failure in that (1) both have experienced overtopping flow, and the outside flanks of moraine dams were being eroded due to the increase of lake water (Figure 1C); (2) both mother glaciers directly terminate in the two lakes; the crevassed snouts and frequent small ice avalanches occurring in the mother glaciers indicate that more large ice avalanches are likely to occur in the near future, which makes the dams more likely to fail; (3) both dams are seeping, and seepage is likely to increase the probability of the dams' failure, as the moraine is unconsolidated in the dams.

The breaching risk assessment variables were selected under the following conditions: (1) the selected variables should provide the most likely breaching values, and (2) the selected indicators should either be summarized from breached moraine-dammed lakes in the Himalayas or be generally used in different regions. According to the two conditions, 11 risk assessment indicators were selected, suggesting that both lakes stayed at "high" risk of failure, as shown in Table 1.

TABLE 2 Estimation of maximum discharge (Q_{max}) from the breach of Longbasaba and Pida lakes. *V* (lake volume) = 1.066×10^8 m^3; P_E (the product of dam height [m], lake volume [m^3] and the specific weight of water [9800 N/m^2] = 1.04×10^{14}J; deviation = (Q_{max}–ΣQ_{max}/7) /ΣQ_{max}/7.

Code	Formulae or models	References	Results (m^3/s)	Deviations
①	$Q_{max} = 0.0048V^{0.896}$	*Popov 1991*	7.5×10^4	59%
②	$Q_{max} = 0.72V^{0.53}$	*Evans 1986*	1.3×10^4	–73%
③	$Q_{max} = 0.045V^{0.66}$	*Walder and O'Connor 1997*	1.0×10^4	–79%
④	$Q_{max} = 0.00077V^{1.017}$	*Huggel et al 2002*	1.1×10^5	133%
⑤	$Q_{max} = 0.00013P_E^{0.60}$	*Costa and Schuster 1988*	3.4×10^4	–28%
⑥	$Q_{max} = 0.063P_E^{0.42}$	*Clague and Evans 2000*	4.9×10^4	4%
⑦	BREACH model	*Fread 1991*	4.0×10^4	–15%

TABLE 3 Parameters used in the BREACH model to simulate the Longbasaba and Pida lakes outburst flood.

Parameters of lakes		Shape parameters of dams[b)]		Attribute parameters of dams	
Item	**Value**	**Item**	**Value**	**Item**	**Value**
Total area (km^2)	2.05	Height (m)	100	Unit weight (kg/m^3)	1700
Total volume (m^3)	1.066×10^8	Width (m)	163	Porosity ratio (%)	36
Average depth (m)	52	Top length (m)	388	Grain size of 50% finer (mm)	32.5
Inflow water of Longbasaba (m^3/s)	6.4[a)]	Bottom length (m)	100	Internal friction angle (°)	32
Inflow water of Pida (m^3/s)	2.8[a)]	Slope of downstream face	1/4	Cohesive strength (kg/m^3)	0
		Slope of upstream face	1/4		

[a)]Averaged values from survey data collected on 1, 6, and 18 August 2005;
[b)]Values for Longbasaba Lake.

Simulations for maximum discharge and breaching properties

The minimum distance between the two lakes is 24 m and all the outflow of Pida Lake seeps directly into Longbasaba Lake; as Pida Lake is 76 m higher than Longbasaba Lake, if Pida Lake fails, the outburst flood will fall into Longbasaba Lake and this sudden flood will destroy the dam of Longbasaba Lake immediately. Therefore, we simulated a GLOF for the two lakes under the "worst-case" scenario, ie Pida Lake breaches first and then Longbasaba Lake breaches almost immediately after.

The estimations of peak discharge (Q_{max}) from the two lakes' failure at the breach dam are shown in Table 2. The calculated values of Q_{max} varied from 1×10^4 to 10^5 m^3/s; the average calculated Q_{max} is 4.7×10^4 m^3/s and deviations [($Q_{max} - \Sigma Q_{max}/7$) / $\Sigma Q_{max}/7$] vary from –79% to 133%.

The hydrograph of floods from the two lakes at the breaching site of the dam was simulated by a BREACH model, using the parameters in Table 3. The results indicate that the outburst flood at the breach of the dam will last for about 5.5 hours, reaching a peak discharge of 4.0×10^4 m^3/s about 1.8 hours after the beginning of the outburst (Figure 3). The final depth, top width, and bottom width of the breach at Longbasaba Lake dam would be about 100 m, 97 m, and 5 m respectively.

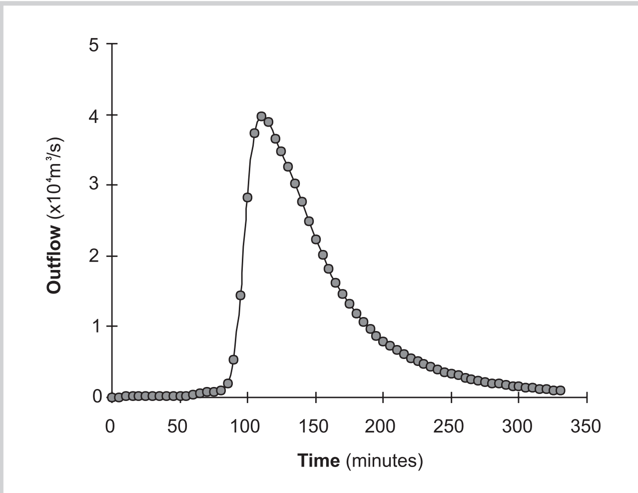
Discussion

Breaching risk assessment

The mechanism of a GLOF is varied and complex; sometimes an outburst flood happens as the result of more than one mechanism (Kershaw et al 2005). It is therefore necessary to examine the various characteristics of breaching risk assessment variables. The field investigations and indicators in Table 1 to evaluate the breaching risk of Longbasaba and Pida lakes include moraine dams, mother glaciers, and climatic setting. To evaluate the probability of an outburst flood, the stability of moraine dams is critical and should be emphasized (McKillop and Clague 2007a).

We evaluated the state of the dams from their shapes and material characteristics. Ice avalanches from mother glaciers are the mechanism most likely to make moraine dams fail in the Chinese Himalayas (Liu and

FIGURE 3 Predicted outburst flood hydrograph for Longbasaba and Pida lakes at the breaching site of the dam, based on the BREACH model.



Sharma 1988). Climate warming may make moraine dams unsteady and accelerate the movement and melting rates of mother glaciers. The relations of lake freeboard and moraine dam height, and lake and mother glacier proximity were also examined. Thus, field investigations combined with the indicators examined various possible breaching risk aspects and can present an actual state of breaching risk for Longbasaba and Pida lakes.

Possible failure mechanisms

Several mechanisms, primarily large ice avalanche, seepage expansion, heavy melting of the mother glacier, the mother glacier sliding into the lake, and extremely high temperatures, were found in the failed moraine-dammed lakes in the Chinese Himalayas (Liu and Sharma 1988). According to a field survey, we think that a large ice avalanche generating shock waves and overtopping flow is the most likely mechanism to make Longbasaba and Pida lakes fail. As expressed above, the crevassed mother glacier snouts and climate warming would enlarge the ice avalanche's size. Second, as the lakes' water levels continue to increase and the overtop flow continues eroding the moraine dams, the two lakes might also fail through overtopping flow incising and destroying the dams. Third, we temporarily conclude that the ice core and seepage is a less likely cause of breach, for there is no evidence that the ice cores have been shrinking and seepage was expanding in the summers of 2004, 2005, and 2006. Yet much attention must be paid to variations in the ice core and seepage in the dams as a result of climate warming.

Simulation of breaching results

The prediction results of Q_{max} for the failure of Longbasaba and Pida lakes varied considerably with different formulae (Table 2).The deviations possibly resulted from original sample lakes of different formulae which were characterized by different attributes of location, area, moraine dam, and breaching mechanism. Theoretically, the greater the similarity between the sample moraine lakes in a formula and the concerned moraine lakes, the more reliable the results of computed Q_{max} expected from the formulae. Generally speaking, if no further analysis of similarities between the sample lakes and the concerned lakes can be provided, the calculated results of Q_{max} would be expected to be more reliable if the compounded variable, PE, is used than if the single variable, V, is used (McKillop and Clague 2007b).

Besides, we arbitrarily considered that the results computed from the BREACH model were relatively acceptable, as the model was set up on the basis of physical mechanisms under the condition of no further verifications. Furthermore, we selected two failed moraine-dammed lakes, Sangwangcuo and Zhangzangbucuo, which failed in 1954 and 1981 respectively, in the Himalayas of China (Figure 1A) as examples to validate the reliabilities of Q_{max} computed using the models

TABLE 4 Verifications of calculated Q_{max}, using two breached moraine-dammed lakes in the Himalayas, Sanwangcuo and Zhangzangbucuo.

Method[a]	Sangwangcuo[b]		Zhangzangbucuo[b]	
	Q_{max} (m^3/s)	Deviation (%)[c]	Q_{max} (m^3/s)	Deviation (%)[c]
⑤	1.04×10^4	–15	1.06×10^4	–50
⑥	2.15×10^4	44	2.88×10^4	45
⑦	1.2×10^4	0	1.8×10^4	12
Indirect measurement	$1–1.3 \times 10^4$	—	1.592×10^4	—

[a] ⑤, ⑥, and ⑦ are models shown in Table 2;
[b] Sangwangcuo: PE=1.5×10^{13}J; Zhangzangbucuo: PE=1.53×10^{13}J;
[c] Deviation = (Q_{max} of calculation–Q_{max} of indirect measurement) / (Q_{max} of calculation).

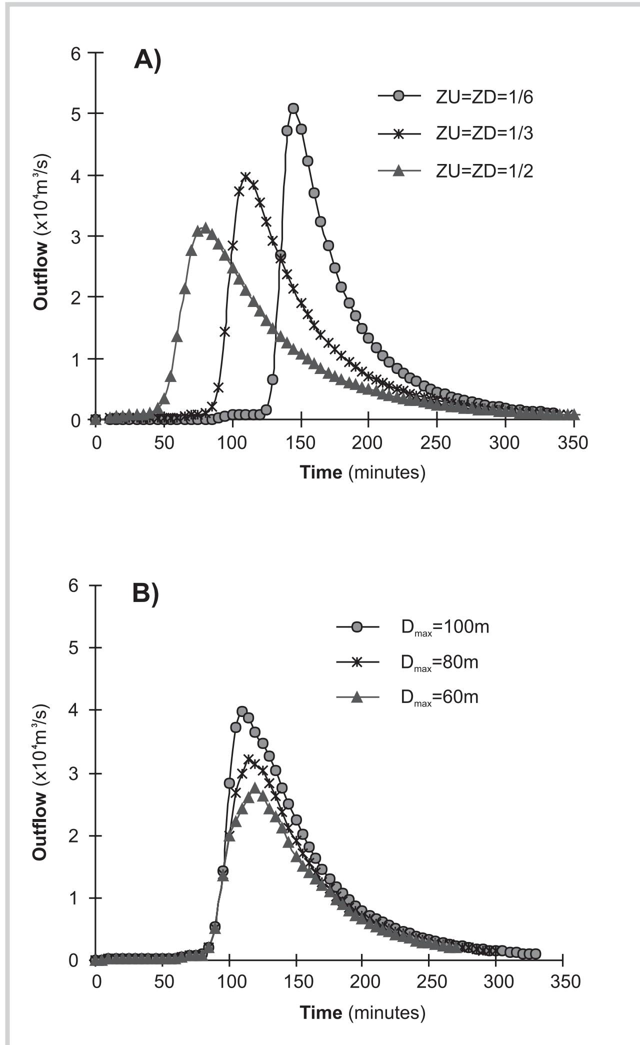
numbered ⑤, ⑥, and ⑦ in Table 2. The variables of Q_{max} and PE of the two lakes were measured indirectly by Xu (1988) and Lu et al (1999). The verification results show that the prediction result using ⑤ is conservative, ⑥ is overestimated, and ⑦ is the closest in comparison to the indirect measurement values (Table 4). In summary, the models numbered ⑤, ⑥, and ⑦ in Table 2 can produce an acceptable prediction range of Q_{max}.

Q_{max} sensitivity tests at the breaching site calculated using the BREACH model with the parameters of Longbasaba and Pida lakes were carried out. The results of the sensitivity analysis show that when the downstream and upstream dam slope changes from 1/3 to 1/6, Q_{max} increases about 22%, and the time until maximum discharge is reached is postponed by about 30 minutes. If the maximum breaching depth were reduced by 20 m near the dam, then Q_{max} would be reduced about 16–19%, and if the inflow increased 30%, Q_{max} would increase 5%. In addition, changing the shape of lake area depth and the value of material parameters of the dam about 30% would usually influence Q_{max} less than 5%. Thus, in the BREACH model, dam slope and maximum breaching depth are the most sensitive parameters to Q_{max} at the breaching site (Figure 4).

As far as the outburst flood hydrograph at the breaching site (Figure 3) is concerned, it seems that the hydrograph reaches its climax abruptly. We suggest two possible explanations for this abrupt shape of the hydrograph. First, the dam slope downstream of Longbasaba Lake (1/4) is somewhat less steep, which might make the outburst flood hydrograph sharper, as shown in Figure 4. Second, we tried to predict the magnitude of Q_{max} under the most dangerous events, so the two lakes are supposed to fail completely and Pida Lake's outburst flood is assumed to join an outburst flood of Longbasaba Lake almost immediately; hence the two coalescing outburst floods would likely make the hydrograph climax steeper.

Furthermore, we compared our hypothetical results with results of investigations of the breached moraine-dammed lakes of Sangwangcuo (Zhang and Liu 1994) and Zhangzangbucuo (Xu 1988) in the Himalayas (Figure 1A), to verify the reliability of the failure properties of Longbasaba and Pida lakes predicted by the BREACH model. The results showed that the calculation values and measured values were close (Table 5). Therefore, the BREACH model is the preferred physically based model to predict the failure properties of Longbasaba and Pida lakes.

FIGURE 4 A) Q_{max} sensitivity tests at the breaching site to upstream/downstream slope of dam, ZU/ZD; B) D_{max}: possible maximum outburst depth of breach near the dam.



Feasible mitigation measures

To mitigate the immediate outburst flood hazard of Longbasaba and Pida lakes, it is estimated that the water level would have to decline by 20 m, ie at least 4×10^7 m^3 of lake water would have to be drained out. Two alternative mitigation methods are proposed, based on field investigations. 1) *Siphoning:* it is estimated that at least 50 siphons with a length of 100 m and a diameter of 0.6 m would be needed to drain out 4×10^7 m^3 of lake water in one year. However, it is difficult to transport so many siphons over such a distance on high mountainous roads. 2) *Excavating:* there are two spillways on the left of Geiqu; one previous spillway is 306 m long from Pida Lake to Geiqu, and the other, current spillway is 452 m long, from Longbasaba Lake to Geiqu. The excavation method can be carried out first at the previous spillway from Pida Lake to Geiqu, then at the current spillway from Longbasaba Lake to Geiqu. Since the spillways are evidently depressed and composed with loose moraine material, it seems that excavating is somewhat more feasible than siphoning.

TABLE 5 Verifications of results calculated using the BREACH model, using two failed moraine-dammed lakes in the Himalayas, Sangwangcuo and Zhangzangbucuo.

Item	Sangwangcuo		Zhangzangbucuo	
	Investigation value[a)]	Calculation value	Investigation value[a)]	Calculation value
Final breach depth (m)	40	40	50	62
Peak discharge (m^3/s)	10,000–13,000	12,000	15,920	18,000
Time of peak discharge reached (hr)	< 1	0.5	0.4	0.3
Time of outburst flood experienced (hr)	40	35	1	0.9
Top width of breach (m)	200–300	167	230	200
Bottom width of breach (m)	60	62	60	70

[a)] Source data from Zhang and Liu (1994);
[b)] Source data from Xu (1988).

Conclusions

Field survey results and assessment indexes for moraine-dammed lake failure were employed to assess the failure risk of Longbasaba and Pida lakes. The assessment results show that both Longbasaba Lake and Pida Lake remain at high risk of failure, and that the excavation measure is the most feasible measure to mitigate the danger of immediate outburst flood of Longbasaba and Pida lakes. However, a water-flow regulated dam should be constructed to regulate the lake water flow with valves after the immediate excavation is finished.

Empirical formulae for peak discharge of moraine-dammed breaching and the BREACH model for earthen dam failures were used to simulate the peak discharge and outburst flood hydrograph at the breach site of Longbasaba and Pida lakes. By analyzing and verifying, we believe that an outburst flood from Longbasaba and Pida lakes would last about 5.5 hours and have a peak discharge of about $3–5 \times 10^4$ m^3/s at 1.8 hours after the beginning of the outburst. The final depth, top width and bottom width of the breach at Longbasaba Lake dam would be about 100 m, 97 m and 5 m, respectively.

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