The hazard assessment of glacial lake debris flow: A case study on Dongcuoqu, Luolong County, Tibet

Mingtao Ding, Zemin Gao, Tao Huang, Xiewen Hu*
Faculty of Geosciences and Environmental Engineering, Southwest Jiaotong University, Chengdu 611756, China

*Corresponding author: huxiewen@163.com

Abstract. The development and outbursts of glacial lake debris flow pose threats to downstream infrastructures. Thus, rational assessment of its potential hazards is necessary to mitigate geological hazards along the Sichuan–Tibet railway lines. In this paper, we used logistic regression models and Rapid Mass Movement Simulation methods to assess the multiyear dynamic evolutionary characteristics and outburst risks of the glacial lake and to conduct numerical simulation of the debris flow process. The adopted methodology used remote sensing images from the Landsat 1–Landsat 8 series for the period 1973–2018, combined with the pieces of information of the geological expedition in the glacial lake Dongcuoqu, Luolong County, Tibet, China. The results revealed that the probability of collapse risk of the Dongcuoqu glacial lake dam was 0.39, and its risk extent reached level I, which indicates medium hazardousness and severe loss. The debris flow process simulation comprises of four stages: initiation, acceleration, deceleration, and termination. The outburst floods flow through the proposed location of the Sichuan–Tibet railway. Specifically, the flow velocity in the vicinity of the Luolong station of nearly 5 m/s, which poses a significant threat to the safe construction of the railway. In the flood and non-flood periods, the change in the amount of snow and ice melt was distinctive, and the maximum storage capacities of the glacial lake during these periods were 82 × 10⁶ m³ and 60.1 × 10⁶ m³, respectively. These findings suggest that the assessment results can be used as an excellent reference for the reduction of the construction risk of the proposed Sichuan–Tibet railway under disaster stress in glacial lake outburst hazard areas.
Keywords: Sichuan–Tibet Railway; Glacial lake Donguquo; Numerical Simulation; Hazard Assessment

1. Introduction

Global warming has induced snow and ice melt accumulation in the highland glacial area, which caused large glacial lake outbursts, massive destruction of downstream human production and living areas and transportation infrastructure, and geo-ecology (Vuichard, 1987; Xu, 1988; Ding and Liu, 1992; Kattelmann, 2003; Fujita et al., 2009; Benn et al., 2012)[2,12,14,17,27,28]. The Tibetan Plateau is located in the marine glacial region and is a primary site for glacial lake development and distribution. In this region, the ice and snow activities are sensitive to global change (Richardson and Reynolds, 2000)[25]. Over the past 50 years, more than two dozens of large-scale glacial lake outburst flood accidents have occurred in the Himalayas, three-quarters of which have occurred in Tibet (Cui, 2003; Che et al., 2004; Ding, 2006; Chen, 2008; Liu, 2008, 2009; Fujita, 2009; Chen, 2011; Liu, 2012)[3,4,5,8,13,14,19,21]. Therefore, the Tibetan Plateau is the region most severely damaged by glacial lake outburst flood. In addition, it is one of the areas that deserve great attention for research on debris flow disaster (Ding, 2016, 2019a, 2019b)[9,10,11]. Furthermore, the Sichuan–Tibet railway, a century-old construction project in China, crosses the Tibetan Plateau where geological disasters frequently happen. At the same time, there are several glacial lakes characterized by a large-scale and intensive dynamics of the activity. Thus, in this area, potential glacial lake outburst floods may pose a significant safety threat to engineering construction.

Due to the complex geological and environmental conditions in the Tibetan Plateau, on-site experiments to observe the processes of glacial lake outburst and secondary debris flow is not convenient and safe. The original state of the indoor recovery model is not suitable to the field conditions, which causes the outburst flood risk assessment to be inaccurate. However, the use of computer numerical simulation methods has overcome these drawbacks. The Rapid Mass Movement Simulation (RAMMS) is a dynamic statistical analysis model based on Digital Terrain Elevation Data. It was initially developed by the Swiss Federal Institute for Snow and Avalanche Research. The RAMMS includes three main process modules: RAMMS: AVALANCHE, RAMMS: DEBRIS FLOW, and RAMMS: ROCKFALL. Among these three modules, RAMMS: DEBRIS FLOW is the most widely used module as it is capable of high-precision numerical simulation of the rapid movement and accumulation process of debris flow. As of now, its use has been successful in numerous studies.

Benjamin (2010)[1] proposed the comparison of the RAMMS results with real events after the modeling and analysis of the occurrence and potential debris flow events in the Olivone region in Southern Switzerland. Cesca et al. (2008) [6] used the RAMMS to invert a debris flow event in the Dolomites in Italy. Huang et al. (2018) simulated two landslide movement processes in Chenjiaba, which indicated that RAMMS is a quantitative hazard assessment method. Song et al. (2018)[26] analyzed the calculation error of solid matter flush and found that it is minimal. Moreover, after
evaluating the debris flow process at different frequencies in the debris flow gully in Badi Township, Beichuan County, China, using the RAMMS, they suggested that the RAMMS can be used as a guide to prevent outburst risk. Thus, the application of the RAMMS to explore the characteristics of debris flow movement of glacial lake outbursts is feasible.

In this research, the Dongcuoqu glacial lake in Lajiu Township, Luolong County, Tibet, was selected as the subject of the study.

By combining the RAMMS with the use of remote sensing and graphic information system data, we attempted to study the multiyear dynamic evolution characteristics, lake stability, and outburst flood movement of the glacial lake. The findings may be used as a reference to reduce geological disasters in the engineering construction area through the assessment of the risks of glacial lake outburst.

2. Study area

2.1 Geographical situation

The Dongcuoqu glacial lake is located in the southwestern part of Lajiu Township, Luolong County, Chengdu City, Tibet Autonomous Region, China. Its geographical coordinates range from N30°10′–31°50′ to E95°10′–95°50′ (Fig. 1). The Luolong County is approximately 129-km long from east to west and 110-km wide from north to south and covers an area of 8108 km². Situated at an altitude of about 3640 m above sea level, the town of Zituo alongside the Zhuomalangcuo River is the administrative center. It is about 302 km from Chengdu and 1256 km from Lhasa, which is the gateway to eastern Tibet.

![Figure 1. Distribution of the debris flow gullies in the Dongcuoqu glacial lake area](image)

2.2 Natural environment

Luolong County has a highland temperate semi-arid monsoon climate, which is characterized by distinct precipitation in the dry and rainy seasons. According to the meteorological data of the period 1990–2002, which was obtained from the weather station of Luolong County, the average annual temperature in the area is low, about 4.5°C–6.4°C; the highest temperatures are concentrated from...
June to August, reaching 25.5°C–30.1°C; and the lowest temperature occurs from January to February, ranging from −17.5°C to −19.7°C. The total annual rainfall in the region is 372–559 mm, for approximately 104–144 days, which concentrates from June to September. Moreover, the maximum daily rainfall is 14.0–39.2 mm, and the annual evaporation is 1579–2138 mm. Throughout the year, there are 167–207 days of ice and 47–73 days of snowfall.

Luolong County has abundant surface water resources, with more than 100 rivers of different flows and 50 lakes. In particular, the main tributaries include the Nujiang River, the Requ River, the Maqu River, the Zhuomalangcuo River, and the Daqu River. The total flow length and annual runoff amount to 1142 km and 2.7 billion m³, respectively.

2.3 Geological conditions
The topography of Luolong County, which is located in the southeastern part of the Tibetan Plateau and east of the Hengduan Mountains and the Nujiang River basin, is characterized by ravines and gullies and steep road conditions. Its terrain is generally high in the south and low in the north and is sloping in a fan-shaped direction to the northeast. During the long cycle of uplift and subsidence of the earth’s crust, the landscape of steep bedrock mountains coexisting with deep river valleys formed four main landforms: hyper-alpine, alpine, valley, and glacial landform.

Controlled by active tectonics in the Yanshan–Himalayan period and influenced by endogenic forces, the continuous uplift of the Tibetan Plateau led to the formation of upwell mountains. In the later periods, the region evolved into a gently undulating plateau primitive landscape leveled by exogenic authorities. The strata were fractured and folded by tectonics, and the rivers began to form in the early Eocene. Toward the Quaternary period, the new tectonic activity caused the strong vertical differential movement of the earth’s crust, with complex tectonic stresses, and frequent earthquakes.

2.4 Development of glacial lakes and debris flow gullies
The area of the Dongcuoqu glacial lake is about 226 km², and the length of its main gully is about 31 km in the EW direction. The wide opening at the top and the shallow “V” shape at the bottom are the primary morphologies of the gully, which has an average longitudinal slope of about 27.27‰. In the main gully, a large glacial lake developed, with a length of about 7 km in the EW direction and a maximum width of about 0.7 km in the SN direction. Within the drainage basin, the highest and lowest elevations are about 5180 and 3815 m, respectively, and the relative elevation difference is 1365 m. The valley slope on both sides of the main debris flow gully ranges from about 25° to 70°, and the width of the valley ranges from about 20 to 100 m. The original orientation of the gully is generally relatively linear. According to the statistics data, the direction orthogonal to the main gully or obliquely of 20 large sub-gully in the Dongcuoqu area intersects at a high angle. Both sides of the main gully are comprised of several sub-gullies with different levels of evolution. A large number of small gullies are distributed to each sub-gully slope, and its leading-edge fan remains mostly intact in their original topographic form due to less manual alterations.
3. Methods

3.1 Interpretation of remote sensing images with long time scales
Ten sets of non-flood and six sets of flood imagery were filtered from the United States Landsat 1–Landsat 8 long time series (1973–2018) remote sensing image data. Each image is highly accurate and unaffected by cloud obscuration. Through visual analysis and interpretation, we were able to finally evaluate the changes between flood and non-flood periods in the main gully and sub-gullies of the glacial lake for each year (Figs. 2, 3). In the estimation of the glacial lake capacity, the area of the glacial lake multiplied by the average depth was used. We assumed that the gully is a linearly varying straight channel with longitudinal slopes from the upstream boundary to the downstream accumulation boundary. The average depth of the lake and the height of the landslide dam were calculated using the longitudinal profile and glacial lake elevation data of the landslide dam obtained from Google Earth.

3.2 The logistic regression prediction model of the glacial lake outburst
The predictor parameters used for the assessment of glacial lake outburst risk are diverse and regionally specific (Lv, 1999; Huggel, 2004; McKillop, 2007)[16,18,23]. In the 32 survey samples of the glacial lake outburst risk assessment, the logistic regression model present reliably accurate, where there is a correlation between each predictor parameters and the probability of risk (Le et al., 2014)[22]:

$$P = \left[ 1 + \exp \left( 1.895 + 17.556B + 36.641X_1 + 20.658d - 43.884S_g + 0.017A - 0.199X_2 \right) \right]^{-1} \quad (1)$$

In Eq. (1), $B$ (km) denotes the top width of the landslide dam; $X_1$, the ratio of the difference between the lake’s height to the landslide dam’s top surface and the height of the dam; $d$ (km), the distance between the ice tongue and the glacial lake; $S_g$ (%), the slope of the section where the ice tongue is located; $A$ (km$^2$), the glacial lake area; and $X_2$ (km$^2$), the replenished glacial area and snow area. If $P < 0.30$, the probability of glacial lake outburst risk is low; $0.30 < P < 0.50$ indicates an intermediate hazard grade, $0.50 < P < 0.80$ indicates a high hazard grade, and $0.80 < P$ indicates a very high hazard grade.

3.3 RAMMS
The RAMMS can be used to accurately simulate the spatial movement and deformation of fluid in a complex 3D terrain. Its physical model expressing consist of Voellmy–Salm continuous rheological and random kinetic energy (RKE) theories:

$$U_{(x,y,z)} = (U_x(x,y,z), U_y(x,y,z))^T \quad (2)$$
Equation (2) calculates the average sliding velocity of the debris flow; Eq. (3), the value and direction of the debris flow sliding velocity; Eq. (4), the unit vector value of the sliding rate; Eq. (5), the mass balance equation for the average depth of fluid; Eq. (6), the friction coefficient in the rheological model; and Eq. (7), the relationship between the RKE $R$ and the friction coefficients $\mu$ and $\xi$, which in the stochastic kinetic energy model. For more detailed parameters and principles of the model, see Ref. Christen et al. (2010)[7]. The parameter settings of the RAMMS model are presented in Table 1.

**Table 1.** Parameter setting of the RAMMS model

| Parameters          | Density (kg/m$^3$) | Coulomb friction | Lambda | Turbulence friction (m/s$^2$) |
|---------------------|--------------------|------------------|--------|--------------------------------|
| Value               | 1580               | 0.200            | 1      | 200                            |

4. Results and Discussion

4.1 Characteristics of multiyear dynamics of area and storage capacity

Based on the interpretation of the multiyear glacial lake area and storage capacity calculations mentioned above (Figs. 2, 3), we measured the area, length, and average depth of the main gully glacial lake, which were 0.26 km$^2$, 6.59 km, and 40.05 m, respectively. The area of the main gully glacial lake changed significantly during the flood and non-flood periods from 1973 to 2018 (Table 2). During the flood period, the area was approximately 1.51–2.049 km$^2$, and during the non-flood period, it was 1.48–1.72 km$^2$. The area of the glacial lake was the largest during the flood and non-flood periods in the years 2013 and 2015. The flood period storage capacities were $60.4 \times 10^6$–$82 \times 10^6$ and $51.6 \times 10^6$–$60.1 \times 10^6$ m$^3$ in the non-flood period, in which the year with the largest storage capacity in the flood period was 2013, and the year with the largest storage capacity in the non-flood period was 2015.

**Table 2.** Statistics of the area and capacity of the main gully glacial lake
| Year | Indicators          | 1973 | 1976 | 1999 | 2003 | 2008 | 2013 | 2015 | 2016 | 2017 | 2018 |
|------|--------------------|------|------|------|------|------|------|------|------|------|------|
|      | The area during    |      |      |      |      |      |      |      |      |      |      |
|      | the flood period   |      |      |      |      |      |      |      |      |      |      |
|      | km²                |      |      |      |      |      |      |      |      |      |      |
|      | 1973               | -    | -    | 1.87 | 1.75 | 1.51 | 2.04 | 1.88 | 1.77 | -    | -    |
|      | 1976               |      |      |      |      |      |      |      |      |      |      |
|      | 1999               | 1.49 | 1.66 | 1.53 | 1.55 | 1.48 | 1.63 | 1.72 | 1.57 | 1.53 | 1.70 |
|      | 2003               |      |      |      |      |      |      |      |      |      |      |
|      | 2008               |      |      |      |      |      |      |      |      |      |      |
|      | 2013               |      |      |      |      |      |      |      |      |      |      |
|      | 2015               |      |      |      |      |      |      |      |      |      |      |
|      | 2016               |      |      |      |      |      |      |      |      |      |      |
|      | 2017               |      |      |      |      |      |      |      |      |      |      |
|      | 2018               |      |      |      |      |      |      |      |      |      |      |
|      | The capacity       |      |      |      |      |      |      |      |      |      |      |
|      | during the flood   |      |      |      |      |      |      |      |      |      |      |
|      | period              |      |      |      |      |      |      |      |      |      |      |
|      | 10⁶ m³             |      |      |      |      |      |      |      |      |      |      |
|      | 1973               | -    | -    | 0.75 | 0.71 | 0.60 | 0.82 | 0.75 | 0.71 | -    | -    |
|      | 1976               |      |      |      |      |      |      |      |      |      |      |
|      | 1999               | 0.52 | 0.58 | 0.53 | 0.54 | 0.52 | 0.57 | 0.60 | 0.55 | 0.54 | 0.60 |
|      | 2003               |      |      |      |      |      |      |      |      |      |      |
|      | 2008               |      |      |      |      |      |      |      |      |      |      |
|      | 2013               |      |      |      |      |      |      |      |      |      |      |
|      | 2015               |      |      |      |      |      |      |      |      |      |      |
|      | 2016               |      |      |      |      |      |      |      |      |      |      |
|      | 2017               |      |      |      |      |      |      |      |      |      |      |
|      | 2018               |      |      |      |      |      |      |      |      |      |      |

Note: “-” means that the remote sensing image interpretation cannot identify the data.
Figure 2. Interpretation of the glacial lakes during the flood period
A total of 36 small glacial lakes with different sizes were formed in various areas by melting snow and ice distributed in the Dongcuoqu watershed by tributaries (Fig. 4). The largest area of these small glacial lakes was 0.310 km², and the smallest was 0.002 km². Four small glacial lakes had an area larger than 0.1 km². During the flood period, all the glacial lakes in the sub-gully thawed, the small glacial lakes with areas less than 0.1 km² during the non-flood period mostly froze, and those with areas larger than 0.1 km² partially froze.

4.2 Stability analysis of the glacial lake landslide dam

After obtaining six predictor values of the Dongcuoqu glacial lake, we calculated the probability of lake outburst risk by combining the risk prediction model of the Tibetan glacial lake outburst with the remote sensing image interpretation data from the period 1973–2018 (Table 3). The results revealed that the dam’s outburst risk probability was 0.39, which value between 0.3 and 0.5, had the medium risk of the lake outburst according to the model hazard level grade.

| Parameters       | Site                      | $B$  | $X_1$ | $d$ | $S_g$ | $A$  | $X_2$ | $P$  |
|------------------|---------------------------|------|-------|-----|-------|------|-------|------|
| The main gully   |                           | 0.32 | 0.27  | 0.60| 0.10  | 1.82 | 125.60| 0.39 |
The lithology of the debris pile formed by the high levels landslide collapse on both sides of the trench is hard granite. Jurassic granites make up the base of the landslide dam, which is poorly permeable and not susceptible to weathering and erosion. The slope of the entire face and back of the dam, which is characterized by a denser stone between the blocks and a higher coefficient of friction, is less than 10°. No diffusion occurs on the top surface of the dam; however, a perennially stable subsurface seepage channel exists within the dam, which is exposed at about 400 m downstream of the top surface of the dam and has a stable permeable infiltration line (Fig. 5a, b). Due to long periods of erosion caused by glacial lake water, as well as the weak erosion resistance of the excellent particulate material itself, the stockpile was transported and deposited in downstream riverbeds. However, gravel, cobbles, and boulders of coarse gravel diameter continue to accumulate on the dam owing to their high resistance to erosion. As a result, they cannot be transported by flowing water under inadequate hydrodynamic conditions. Based on the findings in the field investigation, the Dongcuoqu glacial lake dam body piles primarily consist of large volume, coarse gravel diameter of landslide sliding rocks, and strong resistance to erosion.

![Figure 5. The glacial lake (a) and stockpiles (b) on both sides of the Dongcuoqu area](image)

By synthesizing logistic regression models with infiltration deformation erosion information and resistance stability analysis, it is discussed that the dam body still has a specific risk of failure under particular operating conditions. However, the dam body exhibits excellent stability against erosion and no signs of deformation. The maximum storage capacity of the glacial lake during the flood period is $82 \times 10^6$ m$^3$. The height of it is about 45 m, which size has reached medium according to the discriminating basis in Section 4.1.1 of the “Criteria for the classification of risk levels of weir lakes” (SL 450-2009), with the Class I riskiness, severe lake outburst loss, and hazardousness.

4.2 Numerical simulation of the main gully glacial lake outburst

We selected the area (1.768 km$^2$) from the debris flow gully to the glacial lake as the location for numerical simulation for the RAMMS: DEBRIS computational module.
The results revealed four movement stages of debris flow after the glacial lake outburst (Fig. 7): (a) The initial movement stage: the glacial lake dam began to collapse as the dam’s stability was altered, which weakened the strength of the dam body under earthquake or rainfall conditions. (b) Accelerated movement stage: the fluid in the debris gully and near the shore sediment to accelerate the downstream due to the sudden increase of the upstream debris flow. (c) Decelerated movement stage: the downstream river slope slowed down, and the drop of the longitudinal slope was only 21.9‰; the gradual decrease in the debris flow velocity due to the low conversion of potential energy to kinetic energy, coupled with the bending deformation of the gully and the blocking of the vegetation to the kinetic energy, contributed to the absorption effect. (d) Terminated movement stage: debris floods were partly deposited in downstream channels to form new small glacial lakes and partially merge into a new channel; the total capacity of outburst flooding was about $70.7 \times 10^6$ m$^3$. Glacial lake outburst floods flow through the location of the proposed Sichuan–Tibet railway, with flow velocities reaching 5 m/s in the vicinity of Chada (Fig. 6), which poses threats to the safe construction of the proposed railroad.
The landslide dam has the possibility of outburst risk under the influence of internal and external forces, such as earthquakes and rainfalls, due to the seasonal change in the water storage volume of the Dongcuoqu glacial lake. A total of 16 sets of images were obtained from Landsat 1–Landsat 8 satellite remote sensing data from the period 1973–2018. These images were used to assess the glacial lake outburst risk in the proposed location of the Sichuan–Tibet railway. By applying the RAMMS and analyzing the preliminary interpretation data, this paper attempted to study the multiyear dynamic changing characteristics of the glacial lake under complex environmental conditions, as well as the debris flow movement process. Based on the research mentioned above and the methodology, three main insights were gained:

(1) The size of the Dongcuoqu glacial lake landslide dam and the flood storage capacity reached the medium-sized, and the dam body had a probability of outburst risk of 0.39, with Class I riskiness grade and a high level of outburst loss and hazardousness.

(2) The debris flow process simulation comprises of four stages: initiation, acceleration, deceleration, and termination. The debris flow crosses downstream the proposed location of the Sichuan–Tibet railway, with a flow velocity of nearly 5 m/s in the Luolong station’s vicinity. This poses safety threat to the construction project.

(3) The location of the Dongcuoqu glacial lake in an extensive watershed covering an area of 226.27 km². The total length of the debris flow gully was about 31.44 km, and the sub-gully developed, with a total of 36 small glacial lake sites within each sub-basin.

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References
[1] Benjamin, S Z, 2010, Murgänge im Torrente Riascio (TI): Ereignisanalyse, Auslösefaktoren und Simulation von Ereignissen mit RAMMS.Debris flows in Torrente Riascio (TI): Quantitative analysis of past events, triggering factors and simulation of past and potential events with the numerical simulation tool RAMMS, Thesis for: Master of Science.
[2] Benn D I, Bolch T, Hands K, et al, 2012, Response of debris-covered glaciers in the Mount Everest region to recent warming, and implications for outburst flood hazards, Earth-Science Reviews, 114(1): 156-174.
[3] Cui P, Ma D T, Chen N S, Jiang Z X, 2003, Glacial lake outburst debris flow formation, evolution and mitigation measures, Quaternary Research, 23(6): 621-627(in Chinese).
[4] Che T, Jin R, Li X, et al, 2004, Glacial lakes variation and the potentially dangerous glacial lakes in the Pumqu Basin of Tibet during the last two decades, Journal of Glaciology and Geocryology, 26 (4): 397-402.

[5] Chen Z L, Zhu P Y, Dang C, et al, 2008, Hazards of debris flow due to glacier lake outburst in Southeastern Tibet. Journal of Glaciology and Geocryology, 30 (6): 954-959.

[6] Cesca, M, D’Agostino, Vincenzo, 2008, Comparison between FLO-2D and RAMMS in debris-flow modeling: a case study in the Dolomites, Wit Trans Eng Sci, 197-206. 10.2495/DEB080201.

[7] Christen M, Kowalski J, Bartelt P, 2010, RAMMS: Numerical simulation of dense snow avalanches in three-dimensional terrain, Cold Regions Science and Technology, 63(1-2), 1-14.

[8] Chen Z L, Hong Y, Li X Y, 2011, The warning technology of debris flow caused by glacier-lake outburst in Tibetan Plateau, Journal of Mountain Science, 29 (3): 369-377.

[9] Ding M, Heiser M, Hübl J, et al, 2016 Regional vulnerability assessment for debris flows in China—A CWS approach, Landslides, 13(3): 537-550.

[10] Ding M, Huang T, 2019a, Vulnerability assessment of population in mountain settlements exposed to debris flow: a case study on Qipan gully, Wenchuan County, China, Natural Hazards, 99(1): 553-569.

[11] Ding M, Tang C, Miao C, 2019b, Response analysis of valley settlements to the evolution of debris flow fans under different topographic conditions: a case study of the upper reaches of Min River, China, Bulletin of Engineering Geology and the Environment, 1-12.

[12] Ding Y J, Liu J S, 1992, Glacier lake outburst flood disasters in China, Annals of Glaciology, 180-184.

[13] Ding J X, Shang Y J, Yang Z F, 2006, Cause analysis and quantitative zonation of mudflow hazards along the Rawu-lunang section, Sichuan-Tibet Highway. Journal of Geomechanics, 12 (2): 203-210.

[14] Fujita, K, Sakai A, Nuimura T, et al, 2009. Recent changes in Imja glacial lake and its damming moraine in the Nepal Himalaya revealed by in situ surveys and multi-temporal ASTER imagery. Environmental Research Letters, 4(4): 045205.

[15] Huang T, Ding M, She T, et al, 2017, Numerical simulation of a high-speed landslide in Chenjiaba, Beichuan, China, Journal of Mountain Science, 14(11): 2137-2149.

[16] Huggel C, Haeberli W, Kaab A, et al, 2004, An assessment procedure for glacial hazards in the Swiss Alps. Can, Geotech, 41, 1068-1083.

[17] Kattelmann R, 2003, Glacial lake outburst floods in the Nepal Himalaya: a manageable hazard?, Natural Hazards, 28, 145-154.

[18] Lv R R, 1999, Debris flow and environment in Tibet, Journal of Catastrophology, Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Institute for Traffic Scientific Research of Ministry of Transportation in Tibet, Chengdu: Chengdu Science and Technology Publishing House.
[19] Liu J J, Cheng Z L, Li Y, et al, 2008, Characteristics of glacier-lake breaks in Tibet, Journal of Catastrophology, 23(1), 55-60 (in Chinese).
[20] Liu J J, Cheng Z L, Li Y, et al, 2009, Characteristics of glacier-lake breaks in Tibet, Earth Science Frontiers, 16(4), 372-379 (in Chinese).
[21] Liu J F, Cheng Z L, Chen X Q, 2012, The hazard assessment of glacier-lake outburst in Palongzangbu River from Ranwu to Peilong. Journal of Mountain Science, 30(3): 369-377.
[22] Le M H, Tang C, Z D D, et al, 2014, Logistic regression model-based approach for predicting the hazard of glacial lake outburst in Tibet, Journal of Natural Disasters, 23(5), 177-184.
[23] McKillop R J, Clague J J, 2007, Statistical, remote sensing-based approach for estimating the probability of catastrophic drainage from moraine-dammed lakes in southwestern British Columbia, Global and Planetary Change, 56, 153-171.
[24] Ministry of water resources of the People's Republic of China, 2009, Standard for classification of risk grade of landslide lake, 4-7.
[25] Richardson S D and Reynolds J M, 2000, An overview of glacial hazards in the Himalayas, Quaternary International, 31-47.
[26] Song B, Shen J H, Li J Y, 2018, Application of RAMMS model on simulation of debris flow in the Basha Gully, Journal of Sediment Research, 43(1), 32-37 (in Chinese).
[27] Vuichard D, Zimmerman M, 1987, The catastrophic drainage of a moraine-dammed lake, Khumbu Himal, Nepal: cause and consequences, Mountain Research and Development 7, 91-110.
[28] Xu D M, Ma Q H, 1988, Studies on catastrophes of glacial debris flow and glacial lake outburst flood in china, Journal of Glaciology and Geocryology, 10(3), 284-288 (in Chinese).