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The 1988 glacial lake outburst flood in Guangxieco Lake, Tibet, China

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Abstract. The 1988 glacial lake outburst flood (GLOF) in Guangxieco Lake is studied based on geomorphological evidence, interviews with local residents, field surveys in 1990 and 2007, and satellite images from different years. The findings are as follows. (1) The outburst event was caused by two major factors, namely, intense pre-precipitation and persistent high temperatures before the outburst and the low self-stability of the terminal moraine dam as a result of perennial piping. (2) The GLOF, with the peak discharge rate of $1270\,m^3\,s^{-1}$, evolved along Midui Valley in the following order: sediment-laden flow, viscous debris flow, non-viscous debris flow, and sediment-laden flood, which was eventually blocked by Palongzangbu River. (3) A comparison between the conditions during the outburst in 1988 and the present conditions suggests a small possibility of a future outburst unless drastic changes occur in landscape and climate. Reconstructing the outburst conditions and the GLOF processes is helpful in assessing a potential outburst in glacier lakes in Tibet.

1 Introduction

Glacial lake outburst floods (GLOFs) that carry moraines generally have a high peak discharge rate and cause intense erosion over long distances; they may immediately endanger lives, infrastructure, and power supply (Carey, 2008; Kaltenborn et al., 2010). In the last 2 centuries, devastating GLOFs have become well known worldwide, such as those in the South American Andes (Carey, 2005), the mountains of central Asia (Aizen et al., 1997; Bajracharya et al., 2007; Chevallier et al., 2012; Jansky et al., 2009; Mergili et al., 2011; Narama et al., 2010), North America (Clague and Evans, 1992, 2000; Clague and Mathewes, 1996; Evans, 1987; Evans and Clague, 1994; Moore et al., 2009), and the Himalayas (Cenderelli and Wohl, 1998; Ding and Liu, 1991; Reynolds, 1995; Vuichard and Zimmermann, 1986; Watanbe and Rothacher, 1996).

GLOFs are particularly remarkable in the Tibetan Plateau in China, where tectonic activities are intense, rocks are fragile, and mountains are complex with diverse geomorphology, hydrology, and ecology. A large number of glaciers are widely distributed in the Tibetan Plateau, and the area covered by glaciers is approximately $35\,000\,km^2$, which is approximately 75 % of the glaciers in the Qinghai–Tibet Plateau (Li et al., 1986). With the climate changing from 1980 to 2005, mean glacial thickness in China decreased by 10.56 m (China Meteorological Association, 2006). In addition, glaciers on the Tibetan Plateau have been retreating since the early 20th century (Pu et al., 2004). A number of studies have indicated that the frequency of GLOFs will increase in the coming decades (Mool et al., 2001) and that their effects are likely to extend farther downstream than those that have been experienced to date (Chen et al., 2010; Kaltenborn et al., 2010; Li and Kang, 2006; Liu et al., 2008).

At least 30 GLOFs have occurred in Tibet from 1930 to 2010 (Xu, 1988; Lue et al., 1999; ICIMOD, 2011; Liu et al., 2013), and the present study focuses on GLOFs in

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Guangxieco Lake. This lake is particularly significant because it is the only lake located at an altitude below 4000 m with maritime temperate glaciers that are sensitive to local changes in climate (Li and You, 1992; Chen et al., 2004) and can be traced from the variation of glacier lakes (Yang et al., 2012). Thus far, no detailed and systematic study has yet been conducted on the 1988 GLOF. In this study, the conditions and causes of this GLOF are discussed, and the processes from outburst to flood are reconstructed using geomorphological evidence, interviews with local residents, archived materials, and satellite images from 1981 to 2010.

2 Background

2.1 Study area

Guangxieco Lake lies in Bomê County in southeastern Tibet (Fig. 1). This area has stronger seismic activities, more rainfall, and higher ice temperatures than any other place in Tibet (CSECAS, 1986). The Indian monsoon along Brahmaputra Grand Canyon governs the weather and brings adequate rainfall during summer (Lin and Qian, 2012). The Nyainqêntanglha Mountains and the Brahmaputra, Lancang, and Jinsha rivers are all distributed in this region (Liu et al., 2005). The glaciers in the area account for nearly 8000 km^2, and most of them are maritime temperate glaciers with the equilibrium line located at a (relatively) low altitude and with long melting seasons (Xie and Liu, 2010).

2.1.1 Guangxieco Lake (Midui Lake)

Guangxieco Lake (29°27.83′–29°28.23′ N, 96°29.96′–96°30.14′ E), also known as Midui Lake, is a terminal moraine lake located at an elevation of 3808 m, with dimensions (as measured in 2007) of approximately 680 m in length, 400 m in width, and 14.1 m in maximum depth. The varve and moraine deposits were found to be stacked on the lake bottom, with many layers that have a thickness of approximately 2.6 to 3.0 m, according to field investigations in 1989 (Li and You, 1992) and 2007. As shown in Fig. 2, the lake is dammed by the left and right lateral moraine embankments and two terminal moraine embankments. The left lateral moraine dam is composed of purple-red sandstone and siltstone moraine with a height of 60 to 80 m. The right lateral moraine dam is mainly composed of granite, marble, and limestone with a height of 20 to 50 m. The two terminal moraine embankments are gray, off-white, or sallow. They are covered by minimal vegetation, appear fresh and shallowly weathered, and are composed of loose materials with poor stability. The dimensions of the primary terminal moraine embankment are as follows: an average height of 45 m, a width of approximately 80 m, a length of 320 m, and a slope of 30° downstream. The 1988 dam breach occurred on the left primary terminal moraine embankment as an inverted trapezoid with a top width of about 35 m, a bottom width of approximately 10 m, and a depth of about 17 m.

Two poplars in the lateral moraine dams have been there since 1950 and 1946 based on their annual rings. The other two samples in the secondary terminal moraine embankment have been there since 1984 (information is from the draft of the 1989 field survey by Lv and Li). Therefore, the lateral moraine dams appeared between 1940 and 1950, whereas the secondary embankment was exposed between 1980 and 1990. These phenomena were the results of two strong glacial retreats.

Given the lack of images before the outburst (e.g., from the winter of 1987 through the spring of 1988), the lake in 1988 was found to be higher by 17.4 m than it was in 2007 according to the fieldwork. In this paper, the calculation of the water volumes in different years mainly includes the following steps: (1) through the satellite photograph in different years, the surface area of the lake water on the satellite photograph is drawn. (2) Based on 5 m resolution ratio digital elevation model (DEM) and the calculated water area in the earlier stage, the depth of the water, H, can be deduced. (3) Combined with the ultra-sonic depth finder, the underwater topography map of the Guangxieco Lake was measured and drawn (Yang et al., 2012). Thus, the water volumes can be calculated. In the way, the area of the lake before the outburst was calculated to be 6.4×10^5 m^2 according to the 1980 topographic map and DEM. Simultaneously, assuming that underwater topography did not change, the volume was also calculated to be 69.9×10^5 m^3 according to the cut/fill function of ArcMap and the underwater topographic maps drawn in 2010 (Yang et al., 2012). Using the same method and the thematic mapper (TM) image (27 October 1988), the area and volume of the lake after the outburst were calculated to be 2.3×10^5 m^2 and 9.7×10^5 m^3, respectively.

2.1.2 Gongzo Glacier (Midui Glacier)

Upstream of Guangxieco Lake is Gongzo Glacier (29°23.37′–29°27.33′ N, 96°27.75′–96°30.13′ E), which is also known as Midui Glacier (Fig. 1). Gongzo Glacier has three glacial branches, and their equilibrium-line altitudes run between 4600 and 5000 m (Li and You, 1992). This glacier is a typical maritime temperate glacier with an elevation lower than those of other glaciers in China. The eastern glacier branch occupies 6.21 km^2 above 4300 m, whereas the western glacier branch occupies 11.36 km^2 and connects to the central glacier. The central glacier, which has a total area of 17.18 km^2, has a firm basin, an ice fall, and an ice snout. The firm basin has a chair-like circularity above 4850 m. The ice fall has an altitude of 4100 to 4850 m, a width of 500 to 850 m, a length of 2000 m, and an ice surface slope of 25 to 30°. The ice snout has an elevation of 3800 to 4100 m, a length of 3500 m, a width of 250 to 700 m, a maximum thickness of approximately 70 m, and an ice slope of 2 to 5°. The superglacial moraine that covers the

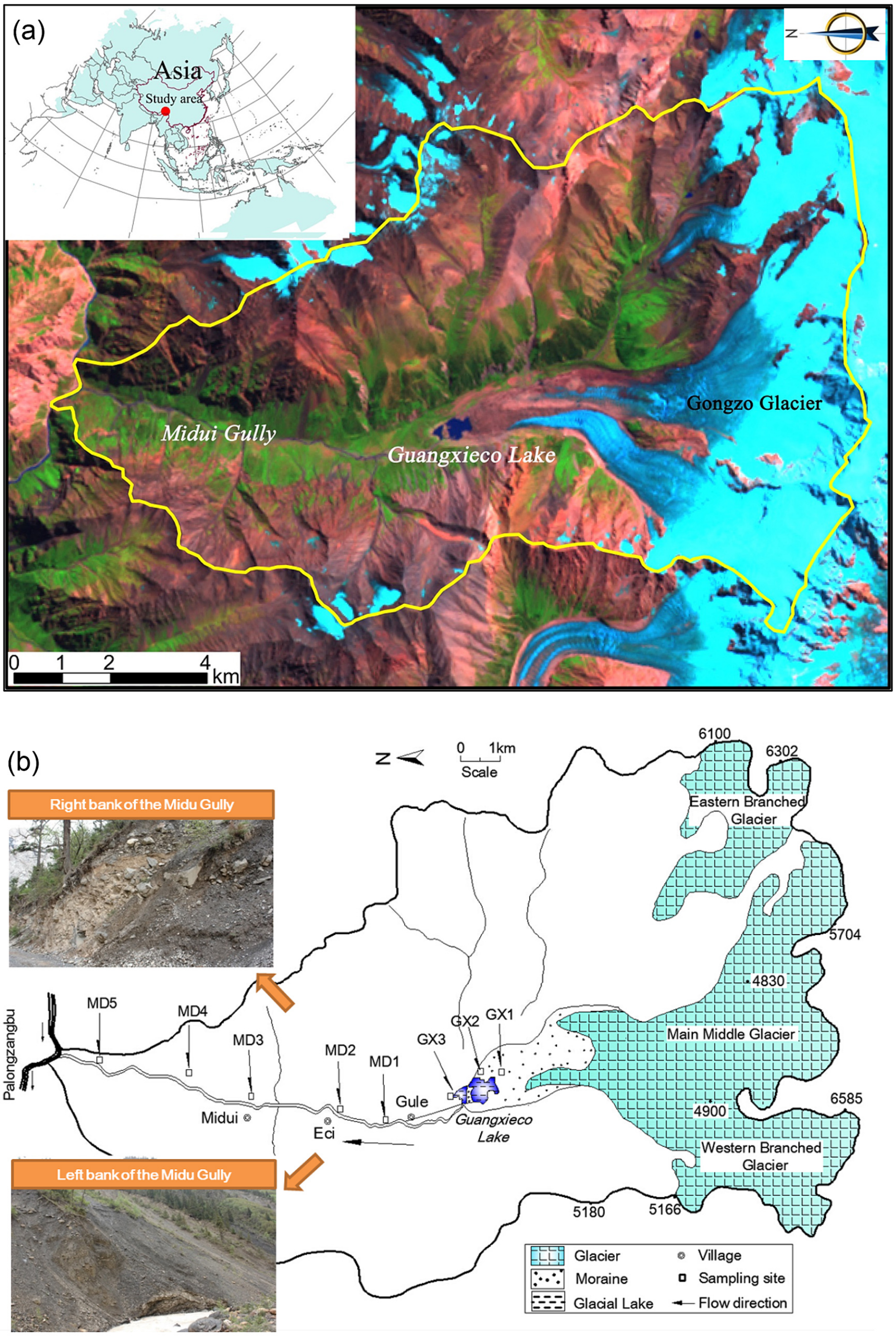

Figure 1. Landscape and background of the study area. **(a)** TM image of 8 September 2005. **(b)** Configuration of the Midui Gully drainage basin (landform is modified from Cui et al., 2010, Fig. 4). Poorly sorted, boulder sediments exposed on both sides of the Midui Gully. The Guangxieco lake soil sampling sites (GX1–3) and the Midui Gully soil sampling sites (MD1–5) are mentioned in Sects. 3.2 and 4.2, respectively.

ice snout is brown and consists of angular granite gravels with diameters ranging from 3 to 10 cm.

2.1.3 Midui Valley

Downstream of Guangxieco Lake is Midui Valley, where a tributary of Palongcangbu River is found. The valley has a drainage area of 117.5 km^2, a length of approximately

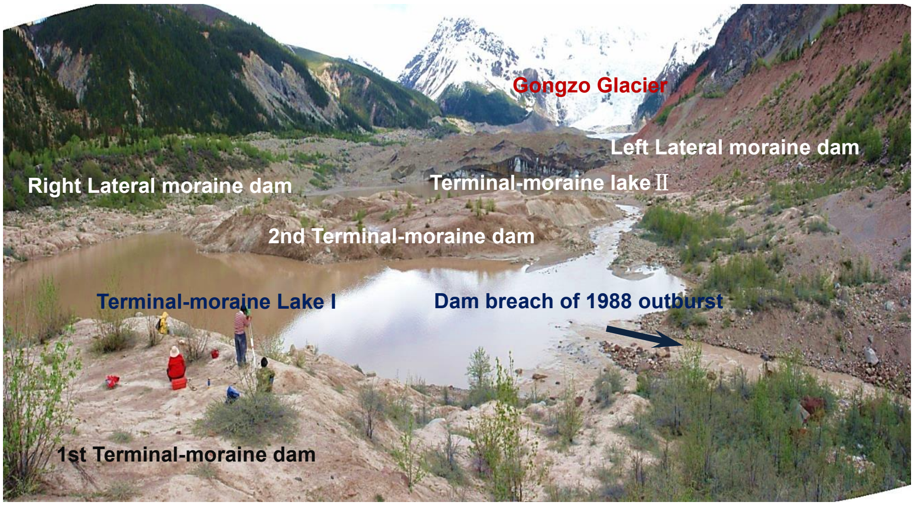

Figure 2. The photo of the Guangxieco Lake in 2007.

7.5 km, and an average gradient of 28.1 ‰ from 3596 to 3810 m. The average runoff ranged from 10 to 12 $m^3 s^{-1}$ on 15 June 2007. Moraine terraces and alluvial materials are widely distributed on both sides of this valley. These materials are made up of a mixture of loose particles with various sizes, such as clay and boulders bigger than 5 m. The main lithology is dense limestone and basalt of the Devonian (D_{2-3}), slate, and schist. A large number of landslides and rockfalls were observed along the narrow channel. Three Tibetan villages are located on the wide and flat land of the valley, namely, Midui, Gule, and Eci, which have approximately 200 inhabitants (Fig. 1).

2.2 GLOF in Guangxieco Lake on 15 July 1988

Guangxieco Lake suddenly burst at 23:30 (China, UTC+8) on 15 July 1988, when an ice avalanche cascaded into the lake and produced a push wave that overtopped the moraine dam and flooded downstream. The lake outburst lowered the lake level by about 20 m and produced a breach of 17.4 m. The outburst contained several million cubic meters of water that rushed into Midui Valley, sweeping materials in its way. Tremendous volumes of sediments were brought into the main tributary of Palongzangbu River, causing a blockage for 0.5 h, which triggered a secondary disaster in the form of a dam break (Li and You, 1992).

The disaster directly killed five people, swept away 51 houses, and destroyed a ranch and a 6.7 ha farm in Midu Village (Luo and Mao, 1995). Secondary flash floods from Palongzangbu River washed away 18 bridges, severely destroyed 42 km of the Sichuan–Tibet Highway, and caused traffic disruptions for 6 months. The total economic cost of the disaster was estimated at over CNY 100 million (Lue et al., 1999).

3 Causes of the GLOF

A lake outburst can be triggered by several factors, including ice or rock avalanches, the self-destruction of moraine dams caused by their slope and seepage from their natural drainage network, earthquakes, and sudden inputs of water into the lake from heavy rains or drainage from lakes located farther up the glacier (Lue et al., 1999; Rai, 2005). Regarding the reasons for the 1988 event, the influence of earthquakes can be excluded because no earthquake was recorded in the last 30 years according to data from the CENC (2014). Then the focus in the following is put on two aspects: climatic observations, including temperature and rainfall fluctuation, and self-stability of the terminal moraine dam.

3.1 Climatic observations

All GLOFs in Tibet took place during the melting season between May and September, which suggests a potential relationship between outbursts and temperature fluctuations (Liu et al., 2011, 2014). Guangxieco Lake is located in a region affected by the Indian summer monsoon, which is the main transfer belt of water vapor that results in most of the precipitation in the Tibetan Plateau. Moisture in the monsoon comes from the Arabian Sea and the Bay of Bengal. After mid-June every year, water vapor transport is significantly enhanced by the monsoon, and rainfall gradually reaches its maximum value throughout the year (Ming, 2007; Lin et al., 2011). In the following analysis, weather data related to temperature and rainfall records from 1960 to 2000 were collected from the nearest weather station in Bomê County.

The analysis showed that precipitation has increased continuously since the 1960s, predominantly from 1960 to 1980. After 1980, however, the increase was no longer obvious. Before the 1988 outburst, some wet years (1982, 1985, and 1987) recorded an annual precipitation of over 1000 mm. In

1988, precipitation reached 1152.6 mm, which is the maximum value in the last 50 years (Fig. 3a). On the eve of the outburst, the total precipitation of 451.2 mm from May to July 1988 increased by 126.4 mm compared with the average in same period from 1980 to 1987 (Fig. 3b). On 4 July, precipitation reached 65.1 mm, which is the maximum precipitation in a day for that year. Intense precipitation may promote glacial accumulation, ice-snout movement close to the lake, and increase in the water level of the lake.

The month of the outburst had an average monthly temperature of 16.6 °C, and was recorded as the hottest month in 1988. This extreme condition combined with high daily temperatures, with 75 continuous days (after 15 May 1988) during which the 5-day moving average temperature was above 10 °C (Fig. 3c). High temperatures may accelerate glacial melting, decrease friction in the ice snout, and facilitate ice avalanche.

In summary, intense pre-precipitation and persistent high temperatures were the climatic cause for the ice avalanche (Li and You, 1992; You and Cheng, 2005) and the Guangxieco Lake outburst.

3.2 Self-stability of moraine dams

Precipitation and temperature fluctuations are the external factors of the outburst; by contrast, the self-stability of the moraine dam, which depends principally on the material composition of the moraines, is the internal cause (Takaji and Yusuke, 2008).

Three sites at 0.5 m below the ground surface were selected for sampling (Fig. 1 and Table 1): the superglacial moraine on Gongzo Glacier (GX1), the lateral moraine on the left lateral moraine dam (GX2), and the terminal moraine on the left side of the terminal moraine dam (GX3) (Liu et al., 2013). Granular analysis shows that the materials are dominated by sand and gravel grains and have almost no clay ($d \leq 0.005$ mm).

The possible types of seepage failure are characterized by the coefficient of uniformity (C_u), the coefficient of curvature (C_c), and the average pore diameter (D_0), as follows:

$$\text{coefficient of uniformity } C_\mathrm{u} = \frac{d_{60}}{d_{10}}, \quad (1)$$

$$\text{coefficient of curvature } C_\mathrm{c} = \frac{(d_{30})^2}{d_{60}d_{10}}, \quad (2)$$

$$\text{average pore diameter } D_0 = 0.25C_\mathrm{u}^{1/8}d_{20}, \quad (3)$$

where d_X represents the grain size that corresponds to X % finer in the grain composition.

Soil is defined as well-graded when C_c is between 1 and 3, as gravel when C_u is greater than 4, and as sand when C_u is greater than 6. Otherwise, soil is poorly graded. In addition, parameters D_0, d_5, and d_3 distinguish the possible types of seepage failure (Yang, 2000).

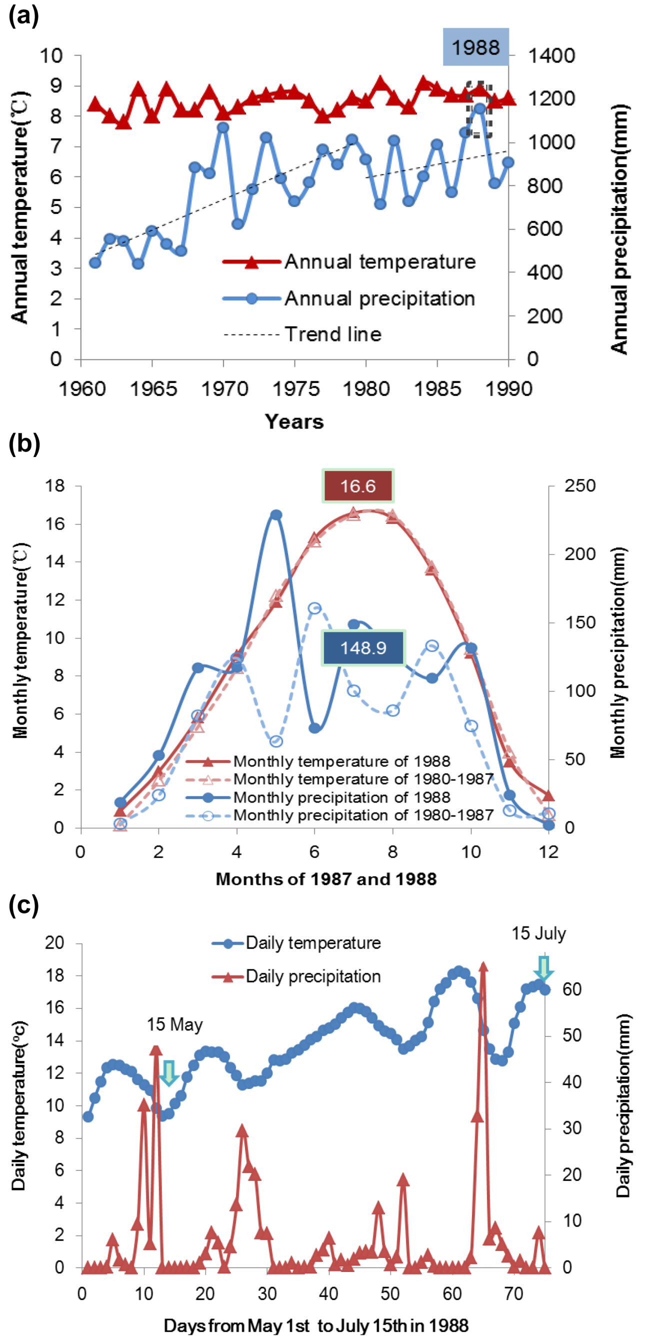

Figure 3. The temperature and precipitation of Bomê County station. **(a)** Annual temperature and precipitation of Bomê County from 1960 to 1990. **(b)** Monthly temperature and precipitation of Bomê County from 1980 to 1988. **(c)** Daily temperature and precipitation of Bomê County before outburst in 1988.

1. Soil flow is most likely to be cohesive, soil and sand with $C_\mathrm{u} < 5$ (or well-graded sand), and gravel with $D_0 > d_5$.

2. Piping is most likely to be poorly graded sand and gravel, with $C_\mathrm{u} > 5$ and $D_0 > d_5$.

Table 1. The grain size distribution of moraines and possible types of seepage failure (Liu et al., 2013).

Sampling no.	Grain size (mm) d_{60}	d_{30}	d_{20}	d_{10}	d_5	d_3	C_u	C_c	D_0 (mm)	Gradation	The type of seepage failure
GX1	6.5	1.5	0.7	0.18	0.08	0.02	36.1	1.92	0.274	Well-graded	Transition type between the two
GX2	6	1.2	0.4	0.15	0.08	0.06	40	1.6	0.159	Well-graded	Soil flow
GX3	28	6	2.5	0.3	0.1	0.05	93.3	4.29	1.10	Poorly graded	Piping

3. Transition between soil flow and piping is most likely to be well-graded sand and gravel, with $d_3 < D_0 < d_5$.

In the preceding analysis, the terminal moraine dam was determined to be poorly graded, and its seepage-failure type was likely to be piping. This conclusion is in accordance with the findings of Li and You (1992). They interviewed local residents in 1990 and speculated the occurrence of perennial piping on the left terminal moraine dam before the outburst. Therefore, piping was conjectured to be the cause of the decline in dam stability for years. When ice avalanches fell into the lake, water pressure multiplied and led to dam failure.

4 GLOF processes

Given that the outburst took place unexpectedly and at midnight, no observation datum was available on the processes of the 1988 GLOF. We attempted to reconstruct the entire process of this GLOF using satellite images, field investigations, and past studies.

4.1 Formation of GLOF

The terminal moraine dam was suddenly overtopped, and the GLOF poured through the outlet breach on the left terminal moraine dam (Fig. 4). By measuring the floodmark sections and using empirical Eq. (4) at 20 s after the outburst, the peak discharge of the GLOF was 1270 $m^3\,s^{-1}$ (Li and You, 1992), which is 150 times more than the mean annual discharge in Midui Valley. Afterward, the discharge exhibited a sharp decline of about 200 $m^3\,s^{-1}$ until the next morning (Fig. 5) (Lue et al., 1999).

$$Q_{\max} = 1.165\left(\frac{L}{B}\right)^{\frac{1}{10}}\left(\frac{B}{b}\right)^{\frac{1}{3}} b(H-h)^{\frac{3}{2}}, \tag{4}$$

where $Q_{\max}$ is the peak discharge of the GLOF ($m^3\,s^{-1}$), L is the length of the lake (m), B is the maximal width of the breach (m), b is the average width of the breach (m), H is the maximal depth of the lake (m), and h is the height of the residual dam (m).

Flow rate variation data are from the Prof. You Yong, one of the investigators in 1992 (Li and You, 1992; Lue et al., 1999). The methods of discharge hydrograph are as follows:

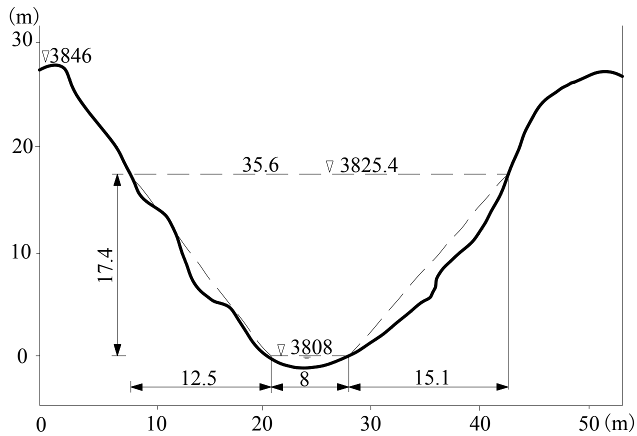

Figure 4. The cross-sectional profile of breach in the Guangxieco Lake (the number is in units of meters and the symbol represents altitude).

1. Interviews were conducted with the local people to know the overflowing time and flood peak time, the rough time of the final discharge and the time of the maximum height of typical sections.

2. Measuring five typical sections the height of floodmark and further the section area, A, could be obtained.

3. The overflow velocity v was deduced by the formula

$$v = \frac{30}{a} h^{\frac{2}{3}} J^{\frac{1}{2}}, \tag{5}$$

   where a represents the comprehensive resistance to debris flow, $a = 1.05\,h^{0.34}$; h represents the height of floodmark and J represents the slope, which both can be actually measured.

4. The discharge Q was calculated according to $Q = A \cdot v$. Finally, the discharge hydrograph can be drawn.

4.2 GLOF evolution along Midui Valley

Moraine terraces and alluvial materials were widely distributed on both sides of Midui Valley. Floods evolved along

Table 2. Five soil-sampling sites in Midui Valley.

Sampling number	Altitude (m)	Latitude N	Longitude E	Height of floodmark section (m)	Clay content (%)	Gradient (%)	μ	D_c	Density (10^3 kg m^{-3})
MD1	3765	29°28.93′	96°29.59′	4.7	0.56	4.52	0.014	6.17	1.48
MD2	3748	29°29.38′	96°29.65′	6	3.44	7.21	0.031	27.03	1.79
MD3	3723	29°30.33′	96°29.74′	6	2.26	1.80	0.029	25.54	1.78
MD4	3714	29°31.02′	96°29.97′	5.7	5.04	0.68	0.020	35.32	1.89
MD5	3634	29°32.05′	96°30.04′	4.5	0.65	4.17	0.011	6.34	1.49

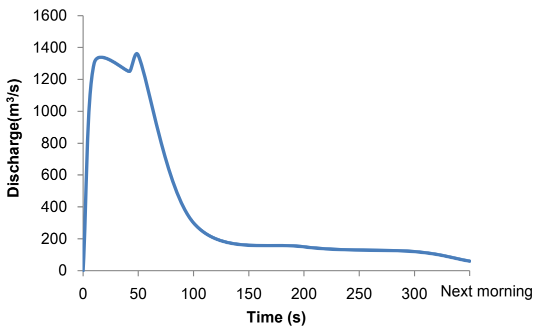

Figure 5. Time–discharge curve of Guangxieco Lake outburst (the data are from Li and You, 1992).

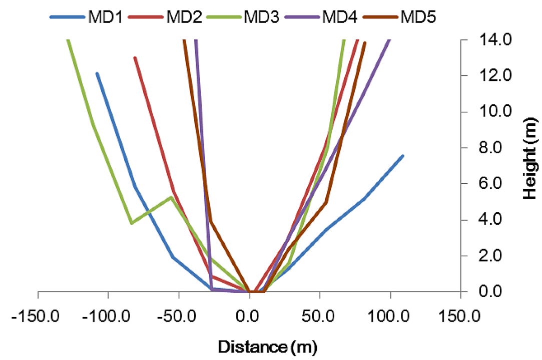

Figure 6. The cross-sectional profiles from section MD1 to section MD5.

the route of Midui Valley, with changes such as the discharge, duration, supply of loose sediments and moraines, and features of the riverbed. After the outburst in 1988, no record on floods existed until 2014. We collected five samples at 0.5 m below the ground surface from section MD1 to section MD5 to determine the evolution of the 1988 GLOF (Figs. 1 and 6).

In Fig. 7, the soil samples were shown to be mainly composed of gravels hat are larger than medium sand. Their clay content ($d < 0.005$ mm) varied remarkably along the valley, i.e., 0.56 % in the MD1 section and 5.04 % in the MD4 section (Table 2). Changes in particle composition reflect possible changes in sediment supplies and alternate density of floods.

Density of the resulted flow can be estimated from the grain size distribution, which can be expressed by Eq. (6). Then the flow density can be calculated by Eq. (7) (Li et al., 2013).

$$P(D) = C D^{-\mu} \exp\left(-D/D_c\right), \tag{6}$$

$$\rho = k \cdot \exp(-2.28\mu) + 0.48 D_c^{0.25}, \tag{7}$$

where $P(D)$ is the percentage of grains $> D$ (mm), μ is a power exponent, D_c is the characteristic size (mm), ρ is the density of flow (10^3 kg m^{-3}), and k is a correction coefficient for counting loss of fine grains. Based on our experiences with debris flows, k is set as 0.75 for moraine materials, and flow density is calculated in Table 2.

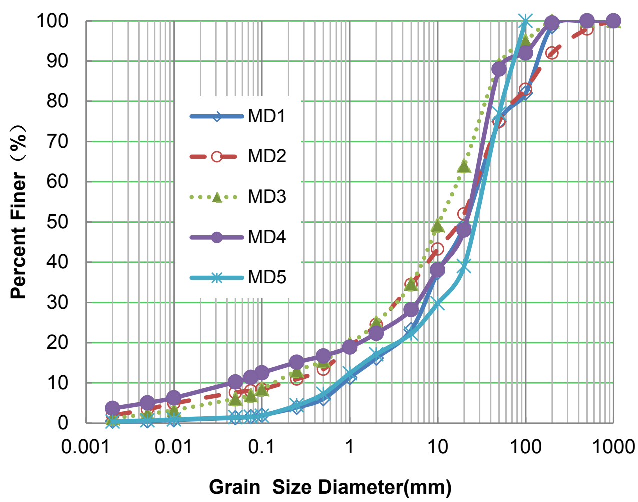

Figure 7. The grain size distribution of soil samples of Midui Valley (the horizontal axis is in log scale).

Flows can be classified according to their densities (Fei and Shu, 2005): sediment-laden flow with $\rho < 1.5 \times 10^3$ kg m^{-3}, viscous debris flow with $\rho > 1.8 \times 10^3$ kg m^{-3}, and sub-viscous debris flow with 1.5×10^3 kg m$^{-3} < \rho < 1.8 \times 10^3$ kg m^{-3}. Therefore, we can draw the following conclusions on the 1988 GLOF.

Table 3. The parameters of the Guangxieco Lake in 1980, 1988, 2001, 2007, 2009 and 2010.

Time	Area of lake ($10^4\,m^2$)	Water storage ($10^4\,m^3$)	Data source
1980	31.24	535.50	Topographic map (1980–2010)
1988 (before outburst)	64.00	699.00	Li and You (1992)
1988 (after outburst)	22.84	97.17	TM (27 Oct 1988)
2001	20.47	88.53	ETM (23 Oct 2001) and Yang et al. (2012)
2007	22.14	104.69	ALOS (23 Dec 2007)
2009	22.53	106.76	ALOS (12 Nov 2009) and Yang et al. (2012)
2010	23.43	113.08	ALOS (23 Dec 2010)

1. At the beginning of the outburst, suspended colloidal particles were few because materials were transported by hydrodynamic erosion. In the MD1 section, the flood was sediment-laden flow with a small amount of clay.

2. Flow turned into sub-viscous debris flow from MD1 to MD2, and then into viscous flow from MD2 to MD4. In the latter segment, clay content was high because of landslides and collapses. Afterward, sediment-laden flow gradually evolved into debris flow and moved to the eastern forest of Gule Village. Then, the flow stopped and deposited sediments with thicknesses ranging from 1.5 and 2.5 m. Granite blocks larger than 1 m were also found in the MD2 to MD4 sections particularly in the MD4 segment, where flow changed into viscous debris flow with high clay content of up to 5.04 %. Numerous boulders carried by the flow could be found in these sections. The largest of these boulders has dimensions of $7.2\,m \times 4.1\,m \times 1.8\,m$ and a weight of 1.46×10^5 kg (Li and You, 1992).

3. High-density debris flow turned into sediment-laden flow with a density of $1.49 \times 10^3\,kg\,m^{-3}$ in the MD5 section, which is 500 m from the junction to Palongzangbu River, because much of the sediments in the flow are deposited as a rocky beach.

4. Sediment-laden flow, which had a discharge rate of $1021\,m^3\,s^{-1}$ and an average rate of $3.8\,m\,s^{-1}$, entered and blocked Palongzangbu River through a dam that was 7 to 9 m high (Chen et al., 2004; Wu et al., 2005).

5 Possibility of future outburst

Comparing the variations in the area and volume of Guangxieco Lake in 1980, 1988, 2001, 2007, 2009, and 2010, the two parameters were found to continuously decrease from 1988 to 2001, and then they increased annually from 2002 to 2010 (Yang et al., 2012). Until 2010, the area and water storage of the lake were only 36.6 and 16.2 % of the values before the 1988 outburst (Table 3). Simultaneously, no piping phenomenon was found on the dam, and an overflow port with a high discharge capacity of about $20\,m\,s^{-1}$ was measured in July 2007. Lastly, the distance between the lake and the ice snout was approximately 870 m in 2014. All evidences indicate a small possibility of a future outburst unless drastic changes occur in local geomorphology or climate.

6 Discussion

6.1 Possibility of a fast-moving glacier

We discussed the external cause and internal cause of outburst based on meteorological factor and stability of dam, respectively. But we found there would be one more outburst reason of advancing movement of the Gongzo Glacier. In our field investigation in 2007, many relics on glacier surface would be determined by the advancing movement of the glacier. A speculation was made that the triggering factor of an ice avalanche may be a fast-moving glacier. Several typical ogives on the ice snout were found below 4200 m; these ogives accompanied the surge as the wave of ice flowed (Xie and Liu, 2010) and a number of tensile crevasses on the surface at an elevation of approximately 3900 m. Rocks with low psephicity, such as breccia, granite, and limestone, were widely distributed around the crevasses. Freshly dead fir trees were also found in this region. These situations are rarely seen in the case of a glacier moving at normal speed, where the grains are round and the trees have been destroyed for years under long-distance transport. Therefore, the observed relics are indicators of a sudden increase in ice movement over a short period (Lønne, 2014). Then it is believed that the Gongzo Glacier was likely to have advanced significantly fast in 1988 and finally resulted in the ice snout falling into the lake and raising the water level substantially. But lacking the necessary satellite images before outburst, we are unable to determine whether the Gongzo Glacier advanced rapidly or not. This discussion part provides a possible reason, which could be the topic of future studies.

6.2 Accuracy of lake volumes

The calculation of depth and volume of lake is readily estimated from DEM, but the estimated values are sensitive to

DEM accuracy (Holmes et al., 2000; Raaflaub and Collins, 2006) and grid cell size (Thieken et al., 1999; Thompson et al., 2001). DEM is a quantitative representation of terrain and is important for Earth science and hydrological applications. DEM accuracy and grid cell size are related intrinsically to the data source and sampling method. This calculation method mainly adopts 5 m resolution ratio DEM, and 5 m spatial resolution ratio determined the level of details of the local topographic relief; namely, the contour interval is 5 m. This may lead to the error in the deduction of water depth and water volume.

7 Conclusions

Guangxieco Lake is a terminal moraine lake influenced by the marine monsoon in southeastern Tibet. The lake burst on 15 July 1988. From the 30 recorded outbursts in Tibet from 1930 to 2010, this incident was the only case that occurred at an elevation below 4000 m (Xu, 1988; Lue et al., 1999; ICIMOD, 2011; Liu et al., 2013). Given that the GLOF in Guangxieco Lake took place unexpectedly and at a high altitude, its reasons and processes remain unclear. In this study, we attempted to review the background and processes of the case.

The two main reasons for the GLOF were determined as follows:

1. intense pre-precipitation and persistent high temperatures before the outburst

   Before the outburst, intense precipitation and persistent high temperatures promoted the melting of the glacier, the possibility of an icefall, the movement of the ice snout close to the lake, and water storage in the lake.

2. low self-stability of the terminal moraine dam by perennial piping

   The terminal moraine dam was composed of poorly graded materials and characterized by perennial piping for many years, which caused its declining self-stability.

The GLOF lasted for approximately 13 h, had peak discharges of 1270 $m^3\,s^{-1}$, and eventually poured water with a volume of approximately $6 \times 10^6\,m^3$ into the lake. The floods evolved along Midui Valley through changes in discharge, duration, supply of loose sediments and moraines, and the features of the riverbed. The order of evolution of the GLOF was as follows: sediment-laden flow, viscous debris flow, non-viscous debris flow, and lastly sediment-laden flood. The latter blocked the main tributary at the junction of Palongzangbu River.

The comparison between the conditions during the outburst in 1988 and the present conditions suggests a small possibility of a future outburst unless drastic changes are made to the landscape and the climate.

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