Glacier Lake Outburst Flood of the Guangxieco Lake in 1988 in Tibet, China

Jing-Jing Liu[1, 2, 3], Zun-Lan Cheng[1], and Yong Li [1]

1. *Institute of Mountain Hazards and Environment & Key Laboratory of Mountain Hazards and Surface Process, Chinese Academy of Sciences & Ministry of Water Conservancy, Chengdu, 610041*;

2. *State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing, 100038*;

3. *Graduate University of Chinese Academy of Sciences, Beijing, 100039*

Correspondence to: Y. Li (ylie@imde.ac.cn)

Abstract

Glacial lake outburst floods (GLOFs) have attracted more and more attention. The Guangxieco Lake burst on 15 July 1988 and its causes and processes were still unclear. We tried to review the reasons for the GLOF and its processes using geomorphological evidence, interviews of the local inhabitants, archive material and satellite images. It was found that: 1) There were three main reasons for the GLOF in 1988: intense pre-precipitation and persistent high temperatures before the outburst, ice avalanche by rapid movement of the Gongzo Glacier and low self-stability of the end-moraine dam by perennial piping. 2) The GLOF with the peak discharge of 1270 m^3/s was evolved along the Midui Valley following sediment-laden flow — viscous debris flow— non-viscous debris flow— sediment-laden flood. Eventually the sediment-laden floods blocked the Palongzangbu River. 3) Comparing the conditions for the outburst in 1988 and at present, the possibility of a future outburst is thought to be small unless the glacier moves rapidly again.

Key words: glacier lake outburst flood, the Guangxieco Lake, reason, process, Tibet

1 Introduction

Glacial Lake Outburst Floods (GLOFs) usually carry a quantity of moraines with the characteristics of high peak discharge and long-distance erosion; they may immediately endanger lives, infrastructure and power supply (Carey, 2008; Kaltenborn et al., 2010). Devastating GLOFs in the last two centuries are especially well known all over the world, such as 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 Zimmerman, 1986; (Watanbe and Rothacher, 1996).

The Tibet Plateau in China is a region with dynamic, fragile, and complex mountain systems as a result of tectonic activity and the rich diversity of its hydrology and ecology. A large number of glaciers are widely distributed in Tibet Plateau, and the area of glaciers is about 35000 km^2, which accounts for 75% of the glaciers in the Qinghai-Tibet Plateau (Li et al., 1986). With climate change, mean glacier thickness in China decreased by 10.56 m from 1980 to 2005 (CMA, 2006), and the glaciers on the Tibetan plateau have been retreating since the early 20th century (Pu and Yao 2004). Indication shows that the frequency of GLOFs will increase in the coming decades (Mool et al., 2001) and that their impacts are likely to extend farther downstream than those experienced to date (Chen et al., 2010; Kaltenborn et al., 2010; Li and Kang, 2006; Liu et al., 2008).

It is estimated that there were at least 30 GLOFs in Tibet from 1930-2010, but numbers are highly uncertain and likely underreported (Xu, 1988; Lv et al., 1999; ICIMOD, 2011; Liu et al., 2013). Among these GLOFs, the GLOF of the Guangxieco Lake was chosen to be studied. It is a unique lake with a maritime-temperate glacier below an altitude of 4000m. The climate reasons for the GLOF of the Guangxieco Lake are mentioned by Li and You (1992) and Chen (2004). Yang et al. (2012) extracted this lake area before and after the outburst by satellite images. But overall, as yet no detailed and systematic geomorphological studies on this typical GLOF have been carried out. In this study, the reasons for the GLOF are discussed and its processes are reconstructed using geomorphological evidence, interviews with local inhabitants, archive material and satellite images from 1981-2010.

2 Background

2.1 Study area

The Guangxieco Lake lies in Yupu Village of southeastern Tibet (in Fig.1); it has stronger seismic activity, more rainfall, and higher ice temperatures than any other place in Tibet (CSECAS, 1986). The Nyainqentanglha, Transverse Mountain, and the Brahmaputra, Lancang and Jinsha River are all distributed in this region (Liu et al., 2005). Southeastern Tibet is influenced by monsoon and has glaciers in an area of nearly 8000 km^2. Many maritime-temperate glaciers, with the equilibrium line at a (relatively) low altitude and long melting seasons, are concentrated in this region (Xie and Liu, 2010).

a. TM image of 2005-9-8

b. Configuration of the Midui Gully drainage basin and the all sites of soil samplings

(GZ 1-3 and MD 1-5) (Landform is modified from Cui et al., 2010, Fig.4)

Fig.1. Landscape and background of the study area

2.1.1 The Guangxieco Lake (Midui Lake)

The Guangxieco Lake (29°27.83'N-29°28.23'N; 96°29.96'E- 96°30.14'E), also called Midui Lake, is an end-moraine lake at an elevation of 3808m, with dimensions of about 680m long, 400m wide, and 10m deep on average, as measured in 2007. According to field investigations in 1989 (Li and You, 1992) and 2007, we found that varve and moraine deposits stacked on many layers on the lake bottom, with a thickness of about 2.60-3.00m. The maximum depth of this lake was measured to be 14.1m (Yang et al., 2012)

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

Figure 2 showed that the Guangxieco Lake was dammed by the left and right lateral-moraine embankments and two grade end-moraine embankments. The left lateral-moraine dam was composed of purple-red sandstone and siltstone moraine with a height of 60m ~ 80m and outer slope of 70 ° ~ 80 °. The right lateral-moraine dam was mainly composed of granite, marble and limestone with a height of 20m ~ 50m. Two end-moraine embankments were gray, off-white or sallow, covered by little vegetation and looked fresh and shallowly weathered, composed of loose materials with poor stability. The dimensions of the 1st terminal-moraine embankment were an average height of 45m, width of near 80m, length of 320m, and a slope of 30° downstream. The dyke breach in 1988 was on the left 1st terminal-moraine embankment, as an inverted trapezoid with a top width of about 35m, bottom width of about 10m and a depth of about 17m.

In lateral-moraine dams, two poplars indicated their ages to be 49 and 53 years by their annual rings, respectively; the other two samples from the secondary end-moraine embankment showed their ages were about 30 years (Lv and Li, 1989). So the lateral-moraine dams were determined to originate between 1940 and 1950 and the secondary embankment exposed between 1980 and 1990, which should be the result of two strong glacial retreats.

2.1.2 The Gongzo Glacier（Midui Glacier）

The Gongzo Glacier (29°23.37'N- 29°27.33'N; 96°27.75'E- 96°30.13'E), also called the Midui Glacier, lies in the upper reach of the Guangxieco Lake (in Fig.1). It is a typical maritime-temperate glacier at a lower elevation than the other glaciers in China. The Gongzo Glacier has three branched glaciers and their equilibrium-line altitudes (ELA) run between 4600m and 5000m. The eastern branched glacier occupied 6.21 km^2 above 4300m, and the western branched glacier occupied 11.36 km^2 and connected to the central glacier. The central glacier's total area was 17.18 km^2, having a firn basin, an ice fall and an ice snout. The firn basin has circularity chair-like above 4850m. The ice fall has an altitude from 4100m to 4850m, a width of 500 ~ 850m, a length of 2000m and an ice surface slope of 25°~ 30°. The ice snout was at an elevation of 3800m ~ 4100m, length of 3500m, width of 250m~ 700m, maximum thickness of about 70m and an ice slope of 2°~ 5°. The superglacial moraine covering above the ice snout was brown and consisted of angular granite gravels of 3cm ~ 10cm in diameter.

2.1.3 The Midui Valley

The Midui Valley connects to the downstream reach of the Guangxieco Lake, which is a tributary of the Ponglongzangbu River. The valley had a drainage area of 117.5 km^2, a length of about 7.5 km and an average gradient of 28.1‰ from 3810m to 3596m. The average runoff was measured to be 10~12 m^3/s on 15 June 2007. On both sides of this valley the moraine terraces and alluvial materials were widely distributed, made up of loose mixture particles of various sizes, from clay to boulders bigger than 5m. The main lithology was dense limestone and basalt of the Devonian (D_{2-3}), slate and schist. A large number of landslides and rock falls were also found along the narrow channel. There are three Tibetan villages, Midui, Gule and Eci, located in the wide and flat land of this valley which had about 200 inhabitants (in Fig.1).

2.2 The GLOFs of the Guangxieco Lake on 15 July 1988

The Guangxieco Lake burst suddenly at 23:30 (China,UTC+8) on 15 July 1988, when a rock and ice avalanche cascaded into the lake and produced an avalanche push wave about 5m high that overtopped the moraine dam and flooded downstream. The GLOF lowered the lake level by about 20m, providing a breach of 17.4 m. It contained several million cubic meters of water and rushed into the Midui Valley sweeping materials on the way. Tremendous volumes of sediments were brought into the main river of the Palongzangbu River causing a blockage for half an hour which triggered a secondary disaster by dam break (Li and You, 1992).

The disaster directly killed five people, swept away 51 houses, and destroyed a ranch and a farm of 6.7 ha in Midu village (Luo and Mao, 1995). The secondary flash floods in the Palongzangbu River washed away 18 bridges, severely destroying 42km of the Sichuan-Tibet Highway, and causing traffic disruption for six months. The total economic cost was estimated at over CNY 100 million (Lv et al., 1999).

3 The reasons for the GLOF in the Guangxieco Lake

A lake outburst can be triggered by several factors: ice or rock avalanches, the self-destruction of the moraine dams due to the dam slope and seepage from the natural drainage network of the dam, earthquakes or sudden inputs of water into the lake e.g. through heavy rains or drainage from lakes further up-glacier (Rai, 2005). Regarding the reasons for this event, earthquakes are excluded because there was no earthquake recorded in the last 30 years depends on the data from China Earthquake Networks Center (CENC). In the following sections, we mainly explore the possible reasons in three aspects: climate changes including temperature and rainfall fluctuation, ice avalanches by movement of the Gongzo Glacier, and the self-stability of the end-moraine dam.

3.1 Climatic observations

All GLOFs in Tibet took place in the melting season between May and September, suggesting a potential relationship between outbursts and climate change (Liu et al., 2014). As for the Guangxieco Lake, data related to temperature and rainfall was collected from the nearest Bomi weather station for 1960-2000.

The analysis showed that precipitation has increased continuously since the 1960s, predominantly from 1960 to 1980. But after 1980, the increase is not obvious. Before the 1988 outburst, there were some wet years with an annual precipitation of more than 1000 mm in 1982, 1985 and 1987. In 1988, the precipitation reached 1152.6 mm, the maximum of the last 50 years (in Fig.3a). On the eve of the outburst, the total precipitation of 451.2 mm from May to July in 1988 had increased by 185.5 mm compared with the same period in the last years (in Fig.3b), and on 4 July, the precipitation reached 65.1 mm, the maximal daily precipitation of that year. Such intense precipitation might promote the glacier accumulation, the ice-snout movement near to the lake, and the water level in the lake.

a. Annual temperature and precipitation of Bomi from 1960-1990

b. Monthly temperature and precipitation of Bomi in 1988

c. Daily temperature and precipitation of Bomi before outburst in 1988

Fig.3. The temperature and precipitation of Bomi station

The outburst month had an average monthly temperature of 16.6 °C, which was hottest month of 1988. Combined with the daily temperature, there were 75 continuous days where the average temperature was above 10 °C by five-day moving average after 15 May 1988 (in Fig.3c). High temperatures might accelerate the glacier melting, decrease the friction of ice snout, and facilitate icefall occurrence.

In summary, the intense pre-precipitation and persistent high temperatures provided the conditions of climatic background for the Guangxieco Lake outburst.

3.2 Movement of the Gongzo Glacier

Interviews with the local inhabitants and the completion of fieldwork, pointed towards ice avalanche as the direct triggering factor of GLOF (Li and You, 1992; You and Cheng, 2005). We supposed that the ice avalanche was caused by rapid movement of the Gongzo Glacier.

Comparing the images and maps of different periods, the distance between the ice snout and the Guangxieco Lake was 940m by MSS image (27 October 1973), 547 m by topographic map (October 1980), 15 m before outburst by Li and You (1992) and 649 m after outburst by TM image (27 October 1988), respectively. It was found that the glacier advanced significantly from

1973-1988. In Figure 4, the topographic map (October 1980) showed that there were left outlet 1 and right outlet 2 on the end-moraine dam. But in TM image (27 October 1988), the outlet 1 and the outlet 2 were disappeared until 2001.

Fig.4. Area variations of the Guangxieco Lake in different periods (It is modified from Yang et al., 2012, Fig.5)

In the field investigation of 2007, there were several typical ogives on the ice snout below 4200m (in Fig.5), accompanying the surge as the wave of ice flow (Xie and Liu, 2010), and a number of tensile crevasses were found on the surface at an elevation of about 3900m. The rocks with low psephicity, such as breccia, granite and limestone, were widely distributed around the crevasses. Furthermore, there were also freshly dead fir trees all over this region. This evidence was rarely seen in the other glaciers at normal movement speed, because the grains should be rounded and the trees should be destroyed under long-distance transport for a few years. Therefore, the tensile crevasses, structure of ogives, rocks with low psephictity and fresh dead trees, were all indicators for a sudden increase in ice movement in a short time period. So we inferred the process of ice avalanche, resulting from the fast-moving glacier. The Gongzo Glacier advanced at high speed which resulted in the ice snout falling into the lake and raising the water level substantially. The increased flow discharges and surges had extra water static pressure and dynamic pressure, strongly impacting the end-moraine dam and eventually causing a breach on the left dam.

Fig.5. The ogives in the Gongzo Glacier (Photo was taken by Lizhen) (Xie and Liu, 2010)

3.3 Self-stability of moraine dams

The fluctuations of climate and the fast moving glacier were both external factors contributing to the outburst in 1988. The self-stability of the moraine dams was an internal cause depending on the moraine composition (Takaji and Yusuke, 2008).

The three sites at 0.5m below ground surface were selected for sampling (in Fig.1): the superglacial moraine on the Gongzo Glacier (GX1), the lateral moraine on the left lateral-moraine dam (GX2), and the end moraine on the left side of the end-moraine dam (GX3), as shown in Table.1 (Liu et al, 2013). Analyzing the grain-size distribution, we found that there were almost no clay minerals ($d \leqslant 0.005$mm) but sand and gravel in domination.

Table 1. Information of sampling sites in the Guangxieco Lake

In soil mechanics, the coefficient of uniformity (C_u), the coefficient of curvature (C_c) and the average pore diameter (D_0) are usually used to characterize the gradation and determine the possible types of seepage failure, defined as,

The coefficient of uniformity $$C_u = \frac{d_{60}}{d_{10}} \quad (1)$$

The coefficient of curvature $$C_c = \frac{(d_{30})^2}{d_{60} d_{10}} \quad (2)$$

The average pore diameter $$D_0 = 0.25 C_u^{1/8} d_{20} \quad (3)$$

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

The soil is defined as well-graded when the coefficient of curvature C_c is between 1 and 3, with C_u greater than 4 for gravels and 6 for sands. Otherwise, it is poorly graded. In addition, the parameters D_0, d_5, d_3 are used to distinguish the possible seepage-failure types (Yang, 2000):

1. Soil flow is most likely to be cohesive soil and sand, with $C_u < 5$;

2. Piping is most likely to be poorly-graded sand and gravel, with $C_u > 5$ and $D_0 > d_5$;

3. Soil flow is most likely to be well-graded sand and gravel with $D_0 > d_5$ and the transition between flow and piping is most likely to be well-graded sand and gravel with $d_3 < D_0 < d_5$.

Table 2. The grain size distribution of moraines and possible types of seepage failure (Liu et al., 2013)

In the analysis above, the end-moraine dam was determined to be poorly-graded and its seepage-failure type was likely to be piping. The conclusion accorded with the findings by Li and You (1992). They interviewed with the local inhabitants in 1990 and speculated perennial piping on the left end-moraine dam before the outburst. So it was speculated that for years, piping caused the decline in dam stability. When ice avalanches fell into lake, the water pressure was multiplied and led to dam failure.

4 The processes of GLOF

As the outburst took place unexpectedly and at midnight, no observation data was available about the processes of the GLOF. We tried to reconstruct the entire process of the GLOF using satellite images, field investigations and past studies.

4.1 The formation of GLOF

With the lack of the images (e.g. winter of 1987 or spring of 1988) before the outburst, the lake of 1988 was higher than it of 2007 to be 17.4 m depend on the fieldwork in 2007. Assuming the boundary of glacier of 1988 was consistent with it of 1990 and combining with the DEM of

1980, the area and volume of lake before the outburst were calculated to be 6.4×10^5 m^2 and 69×10^5 m^3, respectively. by the TM image (27 October 1988), the area and volume of lake after outburst were calculated to be 2.3×10^5 m^2 and 9.7×10^5 m^3, respectively. And it was found that the region of glacier in 1980 was covered partly by the lake after outburst in 1988, and the region of glacier was rapidly disappeared. It also shows that large areas of glacier possibly collapsed into the lake before the outburst in 1988. Lv et al. (1999) estimated that an ice avalanche with a volume of 3.6×10^5 m^3 cascaded into the lake and the average water level was up about 1.4m depending on field surveys of 1997.

The end-moraine dam was instantaneously overtopped, and the GLOF was poured through the outlet breach on the left end-moraine dam (in Fig.6). By measurement of the flood-mark sections, the peak discharges of GLOF were estimated to be 1270 m^3/s using formula 1 after 20s of the outburst (Li and You, 1992), which was 150 times more than the mean annual discharge of the Midui Valley. Then the discharge of GLOF had a sharp decline of about 200 m^3/s until the next morning (in Fig.7). Before the outburst, the volume of the lake reached 6.4×10^6 km^3 and after that, it was only about 1.5×10^6 km^3 (Lv et al., 1999).

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

where L is the length of lake, B is the maximum width of breach, b is the average width of breach, H is the maximum depth of lake, h is the height of residual dam.

Fig.6. The cross sectional profile of breach in the Guangxieco Lake

Fig.7. Time-discharge curve of Guangxieco Lake Outburst

4.2 The evolution of GLOF along the Midui Valley

On both sides of the Midui Valley the moraine terraces and alluvial materials were widely distributed. The floods evolved along the route of the Midui Valley with changes including the discharge, duration, supply of loose sediments and moraines, and features of the riverbed. After the outburst in 1988, there is no record on floods until 2014. We took five samples at 0.5m below ground surface from section MD1 to section MD5 to determine the evolution of the GLOF in 1988, as shown in Fig.1 and Fig.8 .

Table 3. Five soil-sampling sites in Midui Valley

Fig.8 The cross sectional profiles from section MD1 to section MD5

In Figure 9, these soil samples were mainly composed of gravels bigger than medium sands. Their clay content (*d*<0.005mm) varied remarkably along the valley: 0.56% in the MD1 section and 5.04% in the MD4 section (in Table.3). The changes of particle composition reflected the possible changes of sediment supplies and the alternant density of floods.

Fig.9. The particle-size distribution of soil samples in Midui Valley (The horizontal axis is in log scale)

Fei and Su (2005) defined the flood types using its density, e.g. the flood with density less than $1.4\times10^3m^3$ is the sediment-laden flow, the flood with density more than $1.8\times10^3m^3$ is the viscous debris flow and the flood with density between above two is the non-viscous debris flow. From the variation of grain composition, we inferred some characteristics of the flood evolution.

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

with little clay.

2. In the middle and lower segment (MD2-MD4), the deposits from landslides and collapses caused by gravitational erosion and deep weathering, had higher a clay-rich composition. Then the sediment-laden flow gradually evolved into non-viscous debris flow from MD1 to MD2. Next, the debris flow moved into the eastern forest of Gule Village; the flow stopped and deposited in thickness between 1.5m and 2.5m. Granite blocks bigger than 1m were also found in the MD2-MD4 sections, especially in the MD4 segment, where the flow changed into viscous debris flow with high clay content up to 5.04%. In the flood way, available sediments included numerous boulders, of which the largest was measured at the volume of 7.2 m × 4.1 m × 1.8 m and weight of 1.46×10^5 kg (Li and You, 1992). These indications showed that the floods changed into partial-viscous debris flow with great carrying capacity.

3. In the MD5 section, 500m from the junction to Palongzangbu River, much sediment in the flow deposited as a rocky beach and the debris flow of density at 1.89 kg/m^3 eventually turned into a sediment-laden flow of density at 1.41 kg/m^3 (Chen et al., 2004).

4. At the junction to Palongzangbu River, the sediment-laden flow of discharge was 1021 m^3/s and the average rate of 3.8 m/s blocked the main river and formed a dam at a height of 7-9 m (Wu et al., 2005).

5 The possibility of future outburst

Comparing the variations in the area and volume of the lake in 1980, 1988, 2001, 2007, 2009 and 2010, we tried to find out the possibility of a future outburst in the Guangxieco Lake. From 1988 to 2001, the Guangxieco Lake has continuously decreased in water area and storage.

But from 2002 to 2010, its area and storage have increased year by year, accompanied by the retreat of the Gongzo Glacier (Yang et al., 2012). In Table.4, the area and water storage of the glacial lake in 2010 was only 36.6% and 16.2% of the lake before outburst in 1988, respectively.

Table.4 The parameters of the Guangxieco Lake in 1980, 1988, 2001, 2007, 2009 and 2010

In the analysis above, the three main reasons for GLOF in 1988 were intense pre-precipitation and persistent high temperature, rapid movement of the Gongzo Glacier and perennial piping on the left end-moraine dam. At present, there are some phenomena such as an obvious retreat of the Gongzo Glacier, a decrease in the area and water storage of the Guangxieco Lake, no piping phenomenon on the dam and an overflow port with high discharge capacity. This proves that the possibility of a future outburst will be small unless the geomorphology or climate changes, or if the glacier moves rapidly again.

6 Conclusion

The Guangxieco Lake is an end-moraine lake influenced by marine monsoon in southeastern Tibet. It burst on 15 July 1988 and was the only case below a 4000m elevation out of the 30 recorded outbursts from 1930 to 2010 in Tibet (Xu, 1988; Lv et al., 1999; ICIMOD, 2011; Liu et al., 2013). As the GLOF of the Guangxieco Lake took place unexpectedly at high altitude, its causes and processes were still unclear. In this study, we tried to review the reasons for the GLOF and its processes using geomorphological evidence, interviews of the local inhabitants, archive material and satellite images.

The three main reasons for GLOF were found to be:

1) Intense pre-precipitation and persistent high temperatures before the outburst:

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

2) Ice avalanche by rapid movement of the Gongzo Glacier:

Using the satellite images, it was found that the Gongzo Glacier advanced 532m from 1980 to 1988. Before the outburst, the ice snout near to the lake was about 15m but after the outburst the distance was 649m. This proved that the ice avalanche which fell into the lake, was caused by rapid movement of the Gongzo Glacier.

3) Low self-stability of the end-moraine dam by perennial piping:

The end-moraine dam was made up of poorly-graded materials and perennial piping for many years, which led to its declining self-stability. The water pressure, multiplied by the ice avalanche, overwhelmed the end-moraine dam affordability.

The GLOF lasted about 13 hours with the peak discharges of 1270 m^3/s and eventually poured lake water of about 4.9×10^6 km^3 in volume. Along the Midui Valley, the floods evolved through the changes in discharge, duration, supply of loose sediments and moraines, and the features of the riverbed. Its evolvement was by the way of sediment-laden flow —viscous debris flow— non-viscous debris flow— sediment-laden flood. At the junction with the Palongzangbu River, the sediment-laden floods blocked the main river.

Finally, comparing the conditions of the outburst in 1988 and at present, the possibility of a future outburst is thought to be small unless the glacier moves rapidly again.

Acknowledgements

We would like to thank Wu Jishan, Xie Hong and Liu Qiao for their thoughtful revisions of earlier versions of this document. Lv Ruren generously shared unpublished research ideas and insights. Furthermore, this work would not have been possible without the cooperation and trust of local inhabitants along the Midui Valley. We are very grateful to the anonymous reviewers and the associate editors who provided useful comments, which significantly improved the clarity and presentation of the results. This work is supported by the National Natural Science Foundation of China (Grant No.41201010, 41371038), the Directional Projects of IMHE (Grant No. SDS-135-1202-02) and the Open Research Fund of the State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin (Grant No.IWHR-SKL-201209).

References

Aizen, V. B., Aizen, E. M., Melack, J. M., and Dozier, J.: Climatic and hydrologic changes in the Tien Shan, Central Asia, J. Climate, 10, 1393–1404, 1997.

Bajracharya, B., Shresta, A. B., and Rajbhandari, L.: Glacial lake outburst floods in the Sagarmatha region: hazard assessment using GIS and hydrodynamic modelling, Mt. Res. Dev., 27, 336–344, 2007.

Carey, M.: Disasters, development, and glacial lake control in twentieth-century Peru, in: Mountains: Sources of Water, Sources of Knowledge, Springer, Dordrecht, Netherlands, 181–196, 2008.

Carey, M.: Living and dying with glaciers: people's historical vulnerability to avalanches and outburst floods in Peru, Global and Planetary Change, 47, 122–124, 2005.

Cenderelli, D. A. and Wohl, E. E.: Sedimentology and clast orientation of deposits produced by glacial-lake outburst floods in the Mount Everest region, Nepal, in: Geomorphological Hazards in High Mountain Areas, Springer, Dordrecht, Netherlands, 1–26, 1998.

Chen, X. Q., Chen, N. S., and Cui, P.: Calculation of discharge of debris flow induced by glacier lake outburst, Journal of Glaciology and Geocryology, 26, 357–361, 2004 (in Chinese).

Chen, Y., Xu, C., Chen, Y., Li, W., and Liu, J.: Response of glacial-lake outburst floods to climate change in the Yarkant river basin on northern slope of Karakoram mountains, China, Quatern. Int., 226, 75–81, 2010.

Chevallier, P., Pouyaud, B., Mojaïsky, M., Bolgov, M., Olsson, O., Bauer, M., and Froebrich, J.: Trends for snow cover and river flows in the Pamirs (Central Asia), Hydrol. Earth Syst. Sci. Discuss., 9, 29–64, doi:10.5194/hessd-9-29-2012, 2012.

Clague, J. J. and Evans, S. G.: A review of catastrophic drainage of moraine-dammed lakes in British Columbia. Quaternary Sci. Rev., 19, 1763–1783, 2000.

Clague, J. J. and Evans, S. G.: A self-arresting moraine dam failure, St. Elias Mountains, British Columbia, Current Research, Part A: Geological Survey of Canada Paper, Natural Resources Canada, Canada, 185–188, 1992.

Clague, J. J. and Mathewes, R. W.: Neoglaciation, glacier-dammed lakes, and vegetation change in northwestern British Columbia, Canada, Arctic Alpine Res., 28, 10–24, 1996.

CMA (China Meteorological Administration): Climate and Environment in China, Meteorology Press, Beijing, 2006 (in Chinese).

Comprehensive Scientific Expedition to Qinghai-Tibet Plateau, Chinese Academy of Science (CSECAS), 1986. Glaciers in Tibet. Beijing Science Press, Beijing (in Chinese).

Cui, P., Dang, C., Cheng, Z., and Scott, K. M.: Debris flows resulting from glacial-lake outburst floods in Tibet, China, Phys. Geogr., 31, 508–527, 2010.

Ding, Y. and Liu, J.: Glacier lake outburst flood disasters in China, Ann. Glaciol., 16, 180–184, 1991.

Evans, S. G. and Clague, J. J.: Recent climatic change and catastrophic geomorphic processes in mountain environments, Geomorphology, 10, 107–128, 1994.

Evans, S. G.: The breaching of moraine-dammed lakes in the southern Canadian Cordillera, in: Proceedings, International Symposium on Engineering Geological Environment in Mountainous Areas, Science Press, Beijing, 2, 141–150, 1987.

Fei, X. J., & Shu, A. P. Movement mechanism and disaster control for debris flow. Beijing, China: Press of University. Tsinghua, 50-78, 2005 (in Chinese).

ICIMOD: Glacial lakes and glacial lake outburst floods in Nepal. Kathmandu: ICIMOD, 10-12, 2011.

Iturrizaga, L.: Historical glacier-dammed lakes and outburst floods in the Karambar valley (Hindukush-Karakoram), GeoJournal, 63(1–4), 1–47, 2005.

Janský, B., Engel, Z., Šobr, M., Beneš, V., Špaeek, K., and Yerokhin, S.: The evolution of Petrov lake and moraine dam rupture risk (Tien-Shan, Kyrgyzstan), Nat. Hazards, 50, 83–96,doi:10.1007/s11069-008-9321-8, 2009.

Kaltenborn, B. P., Nellemann, C., and Vistnes, I.: High mountain glacier s and climate change. Challenges to human livelihoods and adaption, UNEP/Grid-Arendal, Arendal, 6–9, 2010.

Li, C. and Kang, S.: Review of studies in climate change over the Tibetan Plateau, Acta Geographica Sinica, 61, 327–335, 2006.

Li, D. J. and You, Y.: Bursting of the Midui moraine lake in Bomi, Xizang, Journal of Mountain Research, 10, 219–224, 1992 (in Chinese).

Li, J., Zheng, B. X., Yang, X. J., Xie, Y. Q., Zhang, L. Y., Ma, Z. H., and Xu, S. Y.: Glaciers in Tibet, Science Press, Beijing, 32–37, 1986 (in Chinese).

Liu, J. J., Cheng, Z. L., & Su, P. C.: The relationship between temperature fluctuation and Glacial Lake Outburst Floods in Tibet, China, Quaternary International, 321, 78-87, 2014.

Liu, J. J., Cheng, Z. L., and Li, Y.: Characteristics of glacier lake outbursts in Tibet, Journal of Catastrophology, 23, 54–60, 2008 (in Chinese).

Liu, J. J., Tang, C., and Cheng, Z. L.: The two main mechanisms of glacier lake outburst flood in Tibet, China, Journal of Mountain Science., 10, 239–248, 2013.

Liu, J. J., Tang, C., Cheng, Z. L., and Liu, Y.: Impact of temperature on glacier-lake outbursts in Tibet, Journal of Jilin University (Earth Science Edition), 41, 1121–1129, 2011 (in Chinese).

Liu, S. Y., Shangguan, D. H., Ding, Y. J., Han, H. D., Zhang, Y., Wang, J., Xie, C. W., Ding, L. F., and Li, G.: Glacier variations since the early 20th Century in the Gangrigabu Range, Southeast Tibetan Plateau, Journal of Glaciology and Geocryology, 27, 55–63, 2005 (in Chinese).

Luo, D. F. and Mao, J. Z.: Mountain Hazards and Countermeasures along Southern Sichuan-Xizang Highway (in Xizang), Science Press, Beijing, 105–108, 1995 (in Chinese).

Lv, R. R. and Li, D. J.: Ice-snow-melt water debris flows in the Dongru Longba (Valley) Bomi County, Xizang (Tibet), Journal of Glaciology and Geocryology, 2, 148–160, 1989 (in Chinese).

Lv, R. R., Tang, B. X., and Zhu, P. Y.: Debris flow and environment in Tibet, Chengdu Science and Technology University Press, Chengdu, 106–136, 1999 (in Chinese).

Mergili, M., Schneider, D., Worni, R., and Schneider, J.: June. Glacial lake outburst floods in the Pamir of Tajikistan: challenges in prediction and modeling, in: 5th International Conference on Debris-Flow Hazards Mitigation: Mechanics, Prediction and Assessment, 14–17 June, University of Padova, Italy, 973–982, 2011.

Mool, P., Bajracharya, S. R., and Joshi, S. P.: Inventory of Glaciers, Glacier Lakes and Glacial Lake Outburst Floods, Monitoring and Early Warning System in the Hindu Kush-Himalayan Region, Nepal, International Centre for Integrated Mountain Development, Kathmandu, 5–8, 2001.

Moore, R. D., Fleming, S. W., Menounos, B., Wheate, R., Fountain, A., Stahl, K., Holm, K., and Jakob, M.: Glacier change in western North America: influences on hydrology, geomorphic hazards and water quality, Hydrol. Process., 23, 42–61, 2009.

Narama, C., Duishonakunov, M., Kääb, A., Daiyrov, M., and Abdrakhmatov, K.: The 24 July 2008 outburst flood at the western Zyndan glacier lake and recent regional changes in glacier lakes of the Teskey Ala-Too range, Tien Shan, Kyrgyzstan, Nat. Hazards Earth Syst. Sci., 10, 647–659, doi:10.5194/nhess-10-647-2010, 2010.

Pu, J. C. and Yao, T. D.: Glacier change in the Qinghai-Tibet plateau during the past 100 years. Journal of Glaciology and Geocryology, 5, 517–22, 2004 (in Chinese).

Rai, S. C.: An overview of glaciers, glacier retreat, and subsequent impacts in Nepal, India and China, WWF Nepal Program, Kathmandu, Nepal, 51–60, 2005.

Reynolds, J. M.: Glacial-lake outburst floods (GLOFs) in the Himalayas: an example of hazard mitigation from Nepal, Geoscience and Development, 2, 6–8, 1995.

Takaji, K. and Yusuke, F.: Effect of particle gradation on seepage failure in granular soils, in: Proceedings: Fourth International Conference on Scour and Erosion, C-19, 5–7 November, Tokyo, Japan, 497–504, 2008.

Vuichard, D. and Zimmermann, M.: The Langmoche flash-flood, Khumbu Himal, Nepal, Mt. Res. Dev., 6, 90–94, 1986.

Watanbe, T. and Rothacher, D.: The 1994 Lugge Tsho glacial lake outburst flood, Bhutan Himalaya, Mt. Res. Dev., 16, 77–81, 1996.

Wu, J., Cheng, Z., and Geng, X.: Formation of dam from debris flow in the Southeast Tibet, Journal of Mountain Research, 23, 399–405, 2005 (in Chinese).

Xie, Z. and Liu, C.: The introduction of Glaciology, Popular Science Press, Shanghai, 300–430, 2010 (in Chinese).

Xu, D.: Characteristics of debris flow caused by outburst of glacial lake in Boqu river, Xizang, China, 1981, GeoJournal, 17, 569–580, 1988.

Yang, J.: Soil mechanics, China Water Power Press, Beijing, 60–64, 2000 (in Chinese).

Yang, R., Zhu, L.,Wang, Y., and Chu, D.: Study on the variations of lake area & volume and their effect on the occurrence of outburst of MUDUI glacier lake in southeastern Tibet, Progress in Geography, 31, 1133–1140, 2012 (in Chinese).

You, Y. and Cheng, Z.: Modeling experiment of debris flow in Midui Gully, Tibet, Journal of Mountain Research, 3, 289–293, 2005 (in Chinese).

Table 1. Information of sampling sites in the Guangxieco Lake

Sampling Number	Altitude(m)	Latitude N	Longitude E
GX1	3840	29°27.78'	96°30.27'
GX2	3926	29°28.02'	96°30.29'
GX3	3820	29°28.26'	96°29.94'

Table 2. The grain size distribution of moraines and possible types of seepage failure (Liu et al., 2013)

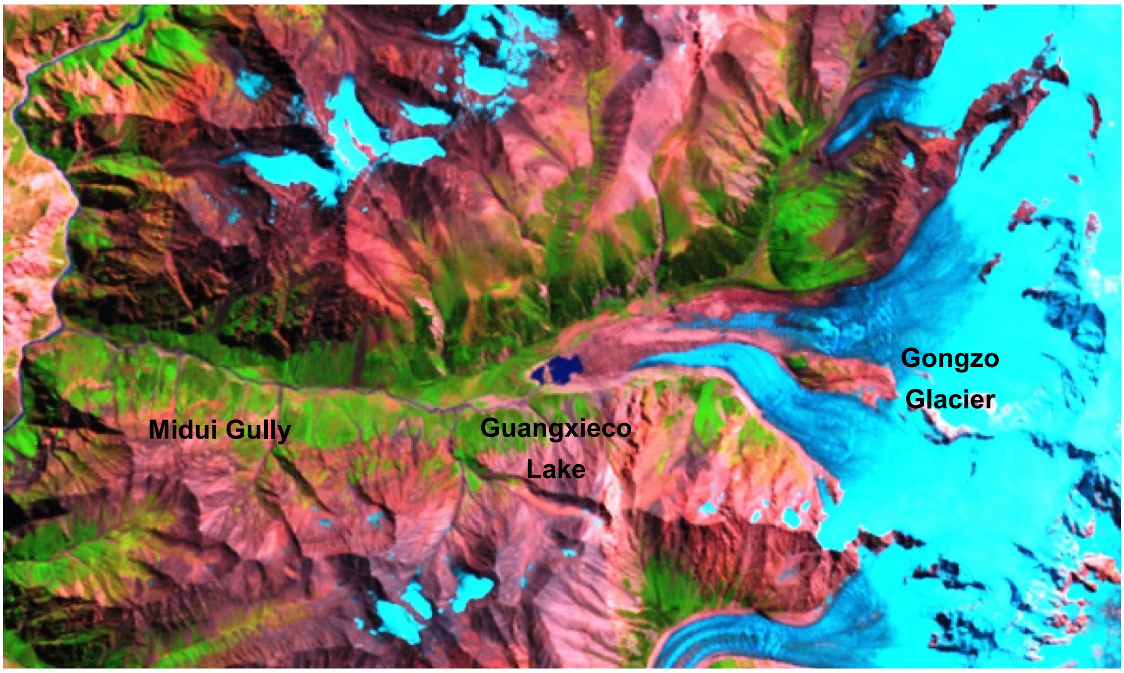
Sampling No.	Grain size(mm)						C_u	C_c	D_0(mm)	Gradation	The type of seepage failure
	d_{60}	d_{30}	d_{20}	d_{10}	d_5	d_3					
GX1	6.5	1.5	0.7	0.18	0.08	0.02	36.1	1.92	0.274	Well-graded	Transition type between the two
GX2	6	1.2	0.4	0.15	0.08	0.06	40	1.6	0.159	Well-graded	Soil flow
GX3	28	6	2.5	0.3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

Table 3. Five soil-sampling sites in Midui Valley

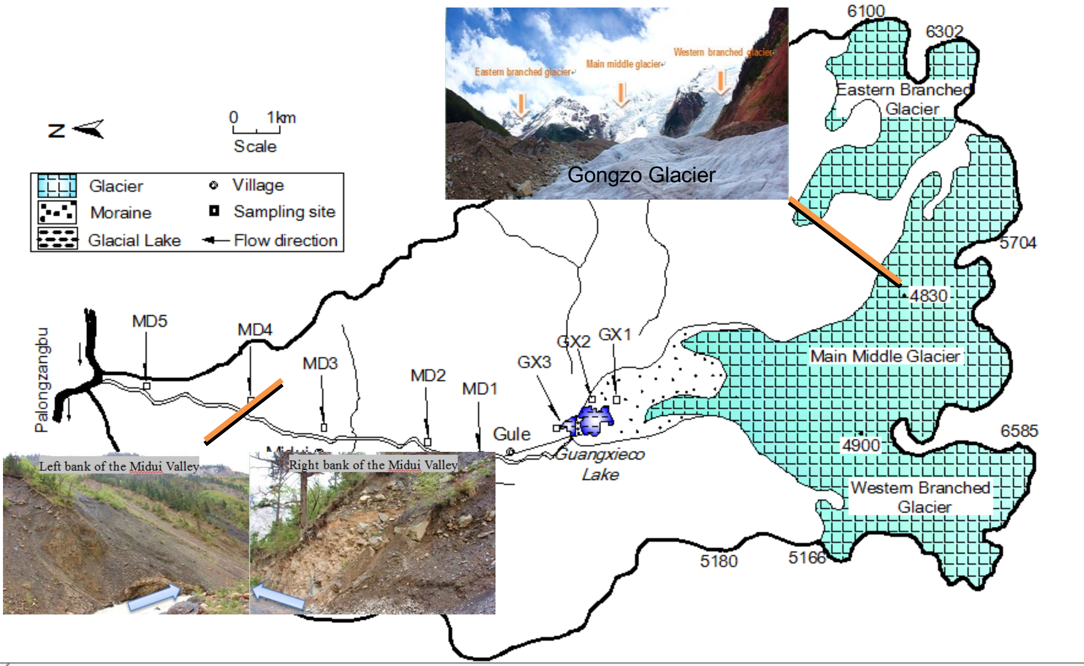
Sampling Number	Altitude(m)	Latitude N	Longitude E	Height of flood-mark section(m)	Clay Content (%)	Gradient (%)	Density (10^3/m^3)
MD1	3765	29°28.93'	96°29.59'	4.7	0.56	4.52	1.58
MD2	3748	29°29.38'	96°29.65'	6	3.44	7.21	1.84
MD3	3723	29°30.33'	96°29.74'	6	2.26	1.80	1.78
MD4	3714	29°31.02'	96°29.97'	5.7	5.04	0.68	1.89
MD5	3634	29°32.05'	96°30.04'	4.5	0.65	4.17	1.41

Table 4. The parameters of the Guangxieco Lake in 1980, 1988, 2001, 2007, 2009 and 2010

Time	Area of lake (10^4m^2)	Water Storage (10^4m^3)	The distance of ice snout to glacier lake (m)	Data source
1980	31.24	535.50	547	Topographic map(1980-10)
1988 (before outburst)	64.00	699.00	15	Li and You(1992)
1988 (after outburst)	22.84	97.17	649	TM(1988-10-27)
2001	20.47	88.53	847	ETM(2001-10-23)
2007	22.14	104.69	780	ALOS(2007-12-23)
2009	22.53	106.76	890	ALOS(2009-11-12)
2010	23.43	113.08	930	ALOS(2010-12-23)



a. TM image of 2005-9-8



b. Configuration of the Midui Gully drainage basin and the all sites of soil samplings (GZ 1-3 and MD 1-5) (Landform is modified from Cui et al., 2010, Fig.4)

Fig.1. Landscape and background of the study area

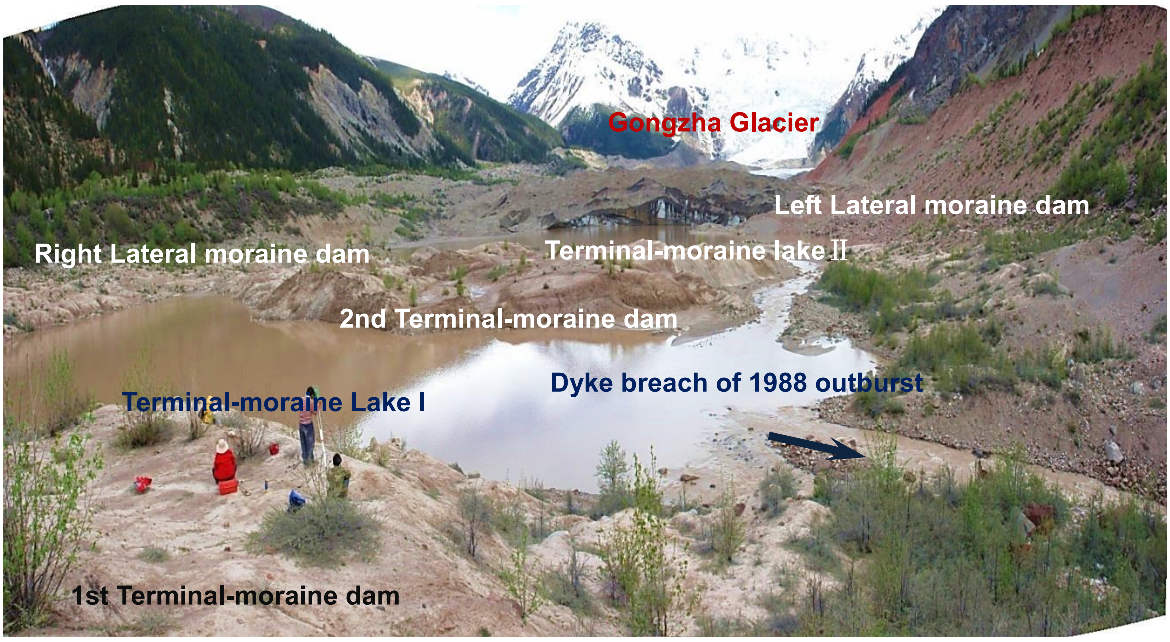
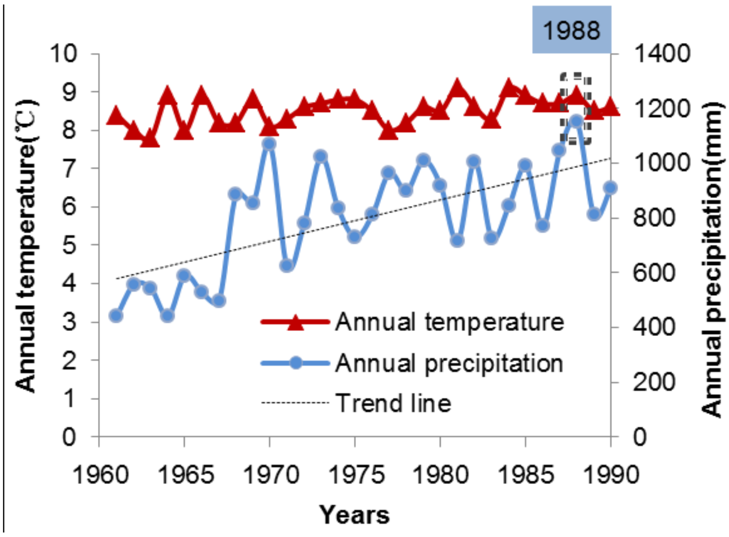
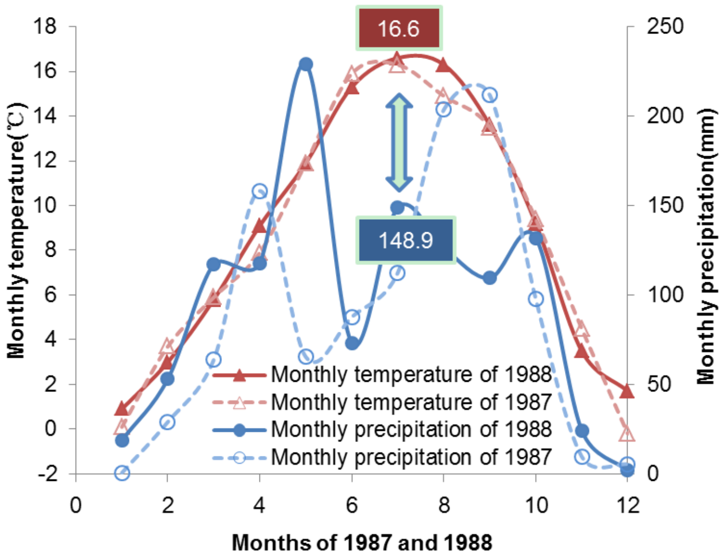


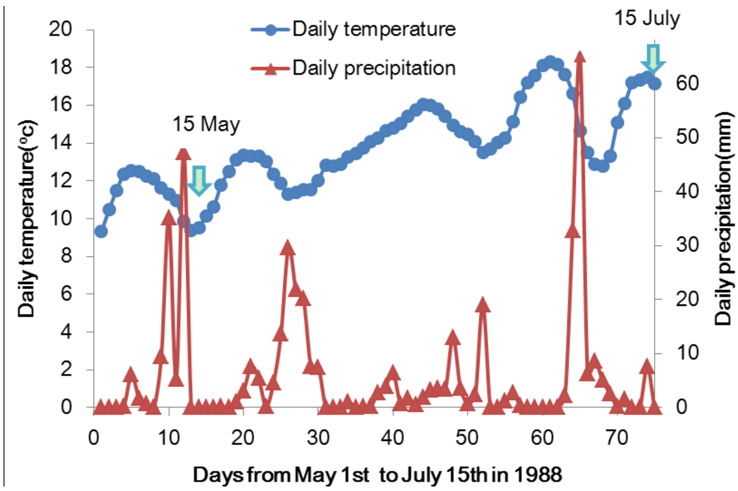
Fig.2. The photo of the *Guangxieco* Lake in 2007



a. Annual temperature and precipitation of Bomi from 1960-1990



b. Monthly temperature and precipitation of Bomi in 1988



c. Daily temperature and precipitation of Bomi before outburst in 1988

Fig.3. The temperature and precipitation of Bomi station

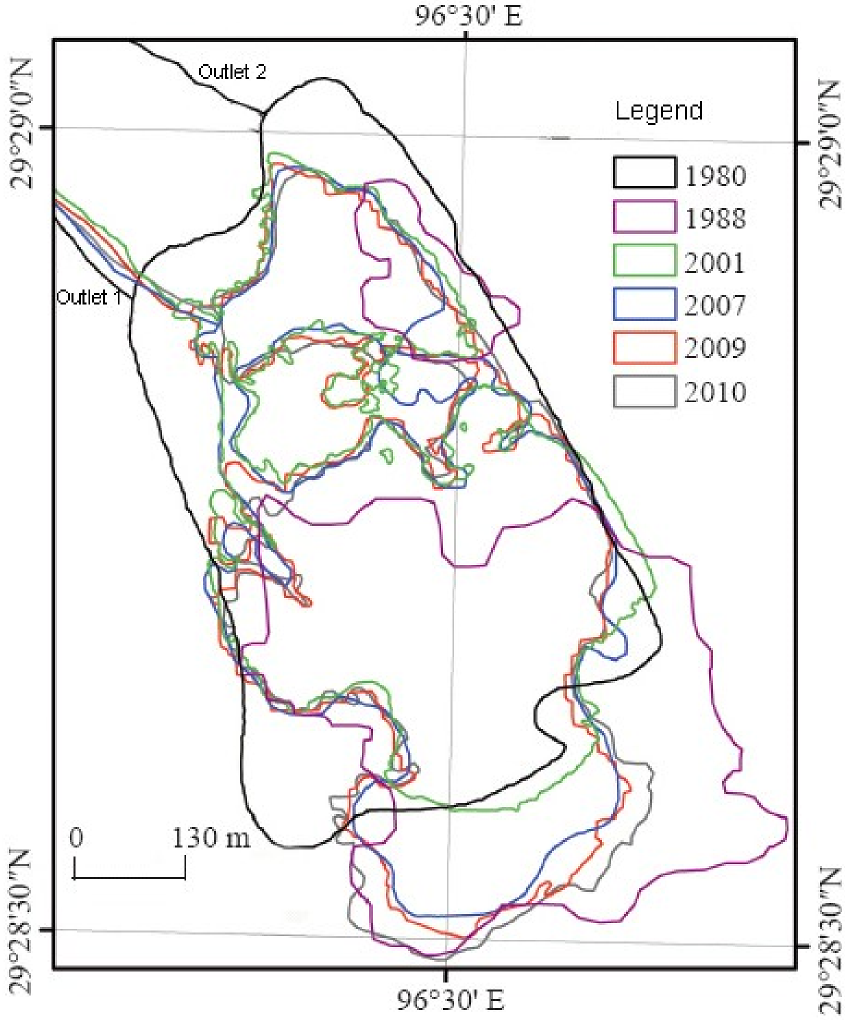


Fig.4. Area variations of the Guangxieco Lake in different periods (It is modified from Yang et al., 2012, Fig.5)

Fig.5. The ogives in the Gongzo Glacier (Photo was taken by Lizhen) (Xie and Liu, 2010)

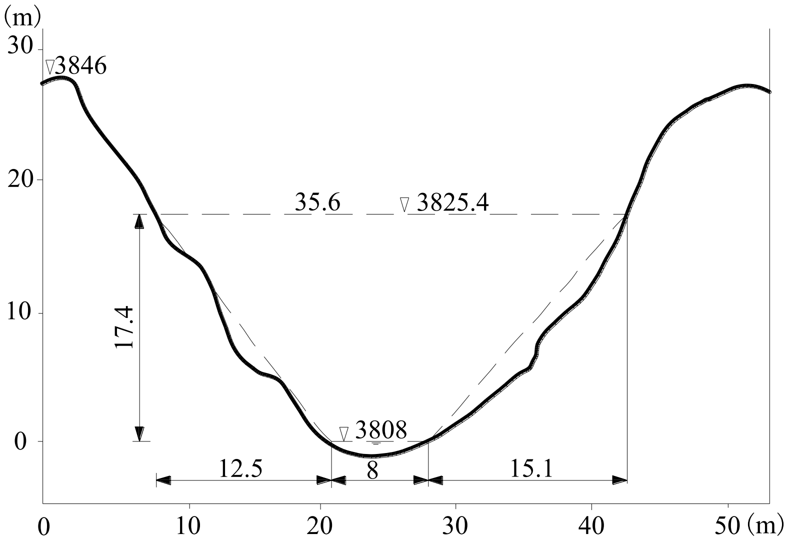


Fig.6. The cross sectional profile of breach in the Guangxieco Lake

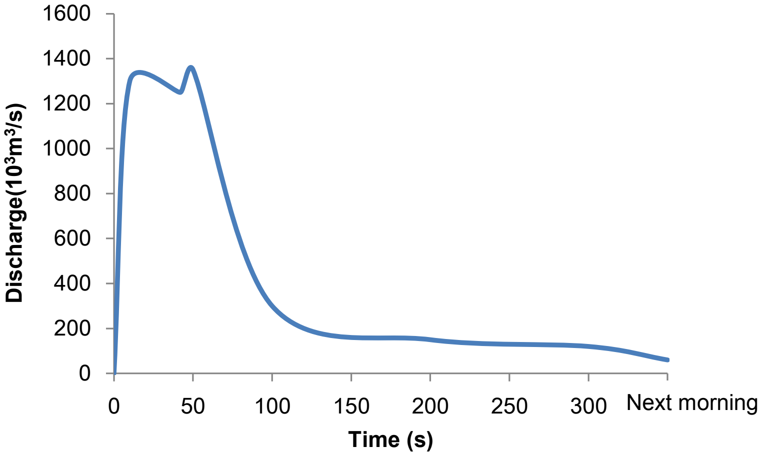


Fig.7. Time-discharge curve of Guangxieco Lake Outburst

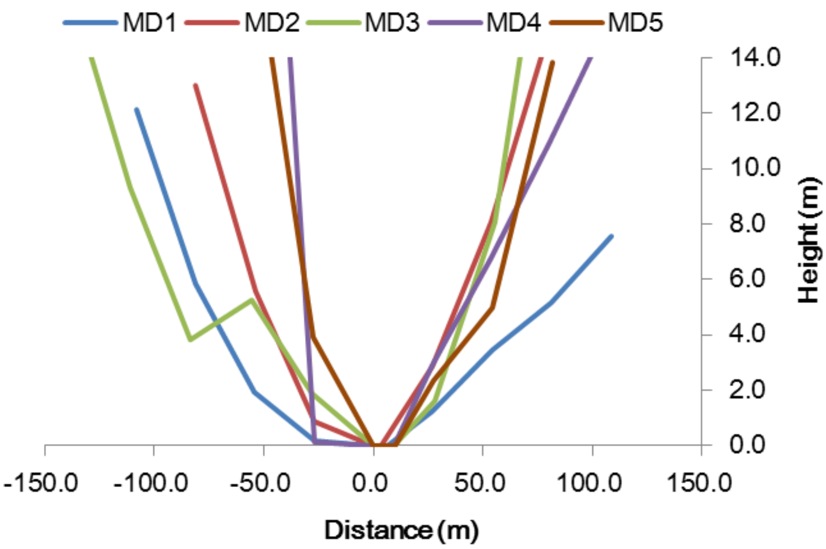


Fig.8 The cross sectional profiles from section MD1 to section MD5

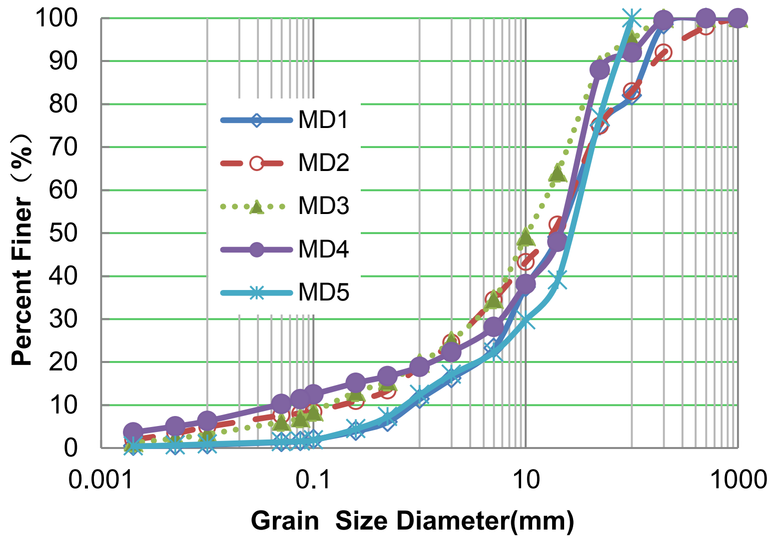


Fig.9. The particle-size distribution of soil samples of Midui Valley (The horizontal axis is in log scale)