Annals of Glaciology 16 1992

Glacier lake outburst flood disasters in China

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ABSTRACT. Floods caused by outbursts from lakes dammed either by end moraines or by glaciers are the most important disasters related to glaciers in China. The former occur mainly in Tibet, and the latter in Xinjiang Province. Exceptionally large outbursts from lakes dammed by end moraines have been reported 19 times since 1935 amd 30 outbursts from glacier-dammed lakes have been recorded since 1956. Outbursts from lakes dammed by end moraines are closely associated with ice avalanches, and 79% of all dam failures occur during July to August when ice avalanches are frequent. Outbursts from glacier-dammed lakes often occur in years of very high air temperature, and 63.3% of all failures are between August and September when the storage capacities of glacier lakes reach their limit. Whether or not the end moraine-dammed lakes are of potential danger depends on the flow of the glacier that feeds the lake and the vertical distance between the terminus of the glacier and the level of the lake. The frequency of periods of outbursts from glacier-dammed lakes corresponds to the periods of glacier advance. During the last 160 years, three periods of frequent outbursts from glacier-dammed lakes have occurred. Their duration has been 20 to 30 years and the interval between them about 40 years. The frequency of glacier lake outbursts could increase early in the next century if glaciers advance and dam up new marginal lakes in response to a cold period since 1940.

INTRODUCTION

Glacier lakes of various sizes and shapes are widely distributed in the western alpine regions of China where the present glaciers are situated. Catastrophic outbursts from glacier lakes, produced by various causes, occur frequently in these regions. Most of them have been ignored as they happened in untraversed regions. However, the known catastrophic outbursts from glacier lakes, as well as meltwater floods and debris flows, have caused severe damage with respect to life and property, farmland, water conservancy, communications, transportation, etc. For example, catastrophic outbursts from glacier lakes in the Himalaya in 1954 inundated hundreds of residential areas, including the cities of Xigaze, Gyangze and Yadong and a number of farmlands, water conservancy and traffic facilities. After the Damenhai glacier lake outburst in Gongbogyernde County in 1964, the flood rushed down with the speed of 10 m s^{-1} from 5120 m a.s.l., headed direct to the mouth of a channel at about 3400 m a.s.l. and lashed at the side of the Niyang River. The debris flow piled up to form a dam in the river valley. The dam was 20 m high, 850 m long and 150 m wide at the top, and it obstructed the river for about ten hours. The flood destroyed the Sichuan–Xinzang highway, cut off the traffic for 20 days, inundated most of four pasturelands and washed away trees on both sides of the gully. In 1981, the Zhongzangbo glacier lake burst and debris flow in Nyalam County smashed the highway for 50 km between the outlet of Zongzangbo gully and the Sun Kosi power station in Nepal. In 1982 the Jinco glacier lake outburst submerged eight villages and a large number of fields, and more than 1600 livestock were killed. In 1984, the Erkuran glacier lake of the Gez river-basin burst, and the debris flow blocked the Gez River and damaged the China–Pakistan highway and a bridge.

With the development of communication, transportation, farming and animal husbandry in the west of China, the disasters which are brought about by outburst floods and debris flows have seriously affected life and property and the economic reconstruction of these regions. Therefore, it is important and urgent to understand the distribution of the dangerous glacier lakes, in order to study the causes of their outbursts and to promote preventive measures. Hence, catastrophic outbursts from glacier lakes have been brought to the attention of scientists, and various types of outburst disasters have been reported and studied during the past ten years (Hewitt, 1982; Lai, 1984; Lu and Li, 1986; Xu, 1987; Xu and Feng, 1988, 1989).

TYPES AND DISTRIBUTION OF THE GLACIER LAKES

Two types of potentially dangerous glacier lakes are known in China. One is the lake dammed by an end moraine and the other is the lake dammed by a glacier. Outbursts from lakes dammed by end moraines occur mainly in the Himalaya, the middle and eastern

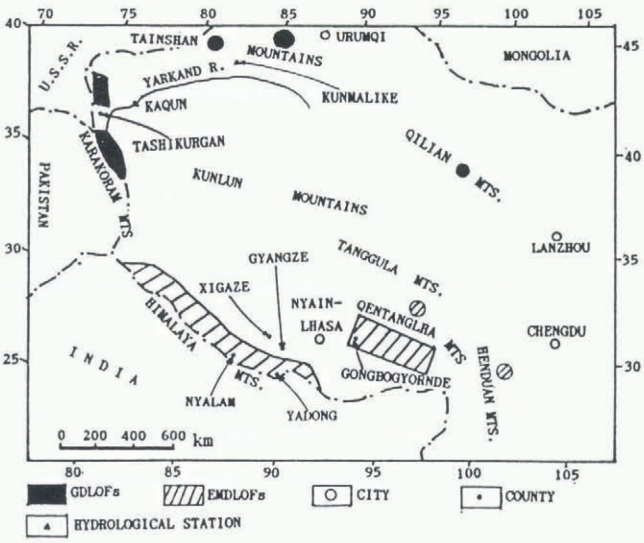

Fig. 1. Distribution of floods from glacier-dammed lakes (GDLOFs) and floods from lakes dammed by end moraines (EMDLOFs).

Nyainqentanglha mountains and sections of the Hengdaun mountains in China (Fig. 1). Up to the present, outbursts from lakes dammed by end moraines happen most frequently in the middle section of the Himalaya (Table 1). Nineteen outbursts from lakes dammed by end moraines have been investigated since 1935. The dams of the end-moraine lakes are made up of various terminal moraines that have formed since the Little Ice Age, of which the youngest moraine lakes, which are close to the present glaciers, are the most dangerous.

Outbursts from glacier-dammed lakes are mainly scattered over the Karakoram mountains, the Pamir and the western Tien Shan mountains in the west of China (Fig. 1). The famous glacier-dammed lakes, Taramkangri and Kyagar, are situated at the upper reaches of the Yarkand River in the Shaksgam valley. Taramkangri and Kyagar Glaciers, both located on northern slopes of the Karakoram mountains, extend to the Shaksgam valley and have dammed up two lakes, 5 km apart (Table 2). These two glacier lakes have burst repeatedly, as recorded at Kaqung hydrological station at the outlet of the Yarkand River since 1954. Up to now, 30 outbursts from glacier-dammed lakes have been recorded since 1956, of which there have been 18 in the Yarkand River, Karakoram mountains, six in the Kunmalike River, Tien Shan mountains, three in the Sikeshu River, Tien Shan mountains (Lai, 1984), two in the Gez River, Pamir and one in the Qilian mountains.

Glacier lakes liable to outbursts are distributed mainly over the mountainous border regions of Qinghai–Xizang Plateau where there are frequent neotectonic movements and high altitudes. The greatest concentration of outbursts from lakes dammed by end moraines is found in the middle Himalaya around Mount Everest. The region where outbursts from glacier-dammed lakes occur frequently is in the Karakoram where the second highest

Table 1. History of outbursts from lakes dammed by end moraines

Lake	*Longitude*	*Latitude*	*Date*	*Flood (F) or debris flow (D)*	*Cause*	*Mountain/river system*
Zhanlonba			1902	F/D		Nyainqentanglha/Yiongzhangbo River
Taraco	86°07′54″	28°17′29″	28 August 1935	D	IA*	Himalaya/Poiqu River
Qubixiama	85°02′24″	27°42′30″	10 June 1940	F	IA	Himalaya/upper Kangma River
Sangwang	90°40′00″	28°24′54″	16 July 1954	F	IA	Himalaya/upper Nyangqu River
Hailuogou	102°00′00″	29°32′00″	July 1955	D		Hengdaun/upper Yalong River
			July 1966	D		
			30 August 1976	D		
Zhangzangbo	85°51′25″	28°10′38″	July 1964	D		Himalaya/Poiqu River
			11 July 1981	D		
Longda	85°00′25″	28°24′46″	25 August 1964	F/D	IA	Himalaya/Trisuli River
Gelhaipu	87°48′31″	27°57′50″	21 September 1964	D	IA	Himalaya/Puqu River
Damenhai	93°09′15″	29°56′20″	26 September 1964	D	IA	Nyainqentanglha/Niyang River
Ayaco	86°29′33″	28°20′49″	15 August 1965	D	IA	Himalaya/Pumqu River
			17 August 1969	D	IA	
			18 August 1970	D	IA	
Bugyai	94°48′36″	31°46′20″	23 July 1972	F		Nyainqentanglha/Nujiang River
Zari	90°48′30″	28°22′50″	24 June 1981	F/D	IA	Himalaya/Pumqu River
Zirema	86°03′54″	28°04′36″	11 July 1981	F/D	IA	Himalaya/Poiqu River
Jinco	87°38′29″	28°11′39″	27 August 1982	D	IA	Himalaya/Pumqu River
Gule	94°30′00″	29°30′00″	15 July 1988	D	IA	Nyainqentanglha/Berongzhongbu River

IA* = Ice avalanche into the lake.

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Table 2. Data for Taramkangri and Kyagar Lakes (Liu Jinshi, 1988, unpublished)

Lake	*Altitude*	*Length*	*Width*	*Volume*	*Maximum depth*	*Length of barrier*	
	m a.s.l.	km	m	$10^8 m^3$	m	km	
Kyagar	4836	4.93	398	0.60	85	1.5	1976–87
	4900	9.48	638	3.15	155		postglacial maximum
Taramkangri	4650	5.25	500	0.96	70	3.8	1976–87
	4672	7.41	610	1.92	90		postglacial maximum

peak in the world, Mount Qogir, is located. Similar lakes in China are mostly situated between 4500 and 5200 m a.s.l. Their areas are under 3 km^2 for the largest ones and only 0.01 km^2 for the smallest ones.

INVESTIGATIONS OF OUTBURSTS FROM GLACIER-DAMMED LAKES

The mechanism of an outburst is complicated, but the external factors that trigger it are obvious. When a glacier lake stores water, its level rises with increasing glacier ablation. Consequently, outbursts from glacier-dammed lakes often occur in years of the highest air temperature (Fig. 2). The volume of most of the outbursts is between 1000 and 3000 $m^3 s^{-1}$. The probable reason why four of the floods reached peaks between 5000 and 6000 $m^3 s^{-1}$ is because two ice-dammed lakes, Taramkangri and Kyagar, burst at the same time. Three of the four largest floods in the Yarkand River, and all floods in the Kunmalike River, happened between 20 August and 30 September, which is over a month later than the maximum ablation period in July. Failure of dams happens mostly between 20 August and 30 September when the storage capacity of the glacier lakes reaches a maximum (Table 3). It might be postulated that the catastrophic outbursts from glacier-dammed lakes can be predicted on the basis of weather forecasts, when satellite images show that the lakes have reached their maximum area.

In general, an ice dam is not frozen to its bed, water from the lake does not flow over the dam and the lake drains through subglacial channels. After the outburst, the dam forms again.

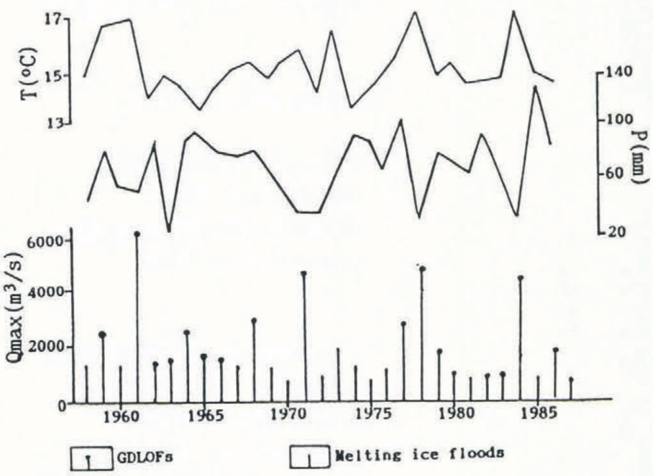

Fig. 2. Peak discharge of glacier outbursts of the Yarkand River at Kaqun Station, mean air temperature in summer and annual precipitation at Tashikurgan Station (3090 m a.s.l.). GDLOFs are floods from glacier-dammed lakes.

POTENTIALLY DANGEROUS END-MORAINE DAMMED LAKES

An end-moraine dam is different from a marginal glacier dam. The latter is composed of ice which easily melts and cracks, but the former is composed of till of various sizes

Table 3. Timing of outbursts from glacier-dammed lakes and outbursts from lakes dammed by end moraines

Date	*Outbursts from glacier-dammed lakes*		*Outbursts from lakes dammed by end moraines*	
	Number	%	Number	%
July to 20 August	7	23.3	11	57.9
20 August to 30 September	14	46.7	6	31.6
after 30 September	7	23.3	0	0
before 1 July	2	6.7	2	10.5
total	30	100	19	100
July	2	6.7	8	42.1
August	11	36.7	7	36.9
September	8	26.6	2	10.5
others	9	30.0	2	10.5
total	30	100	19	100

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Table 4. Glacier lake inventory in the Poiqu and Pumqu basins (Liu, C. H. and Sharmal, 1988)

Type of lake	Lakes number	% of total	Lakes area	% of total	Lakes volume	% of total	Mean area	Mean volume	Mean depth
			km²		km³		km²	10^8 m³	m
cirque	86	31.6	6.56	11.7	0.066	4.4	0.076	0.77	10
rough valley	47	17.3	12.47	22.2	0.312	20.7	0.265	6.63	25
end moraine-dammed	139	51.2	37.09	66.1	1.124	74.9	0.267	8.09	30
total	272		56.11		1.501				

and is normally much more stable than the ice dam. An inventory of existing glacier lakes of the Pumqu and Poiqu Rivers in the Himalaya was made by a Sino–Nepalese expedition investigating glacier lake outbursts in the Himalaya in 1988 (Table 4). Only 3.7% of the total number of the glacier lakes and 7.2% of the end moraine-dammed lakes are dumping glacier lakes.

The following morphological features characterize a dangerous end-moraine dam: it has a closed lake basin, a dam height over 80 m, a ratio of dam height to top width less than 0.6, an angle of slope of the outside of the dam of about 23° and a water depth at the dam over one-third of its height (Xu and Feng, 1989). Further, the dam contains an ice core that may reduce its stability. However, the static pressure maintained by the lake is still not high enough to burst the dam without an additional external action being exerted. The investigated outbursts from lakes dammed by end moraines were all induced by ice avalanches that came from the glaciers feeding the lakes. In each case, an ice avalanche dropped suddenly into the lake; swift and violent waves travelled down the lake, creating breaches in the dam. Because an ice avalanche is associated closely with melting of ice, periods of maximum ablation also are those of frequent ice avalanches. Hence, 79% of all failures of the dams occur during the hottest months of July and August (Table 3).

Whether or not end moraine-dammed lakes are dangerous depends on the flow of the glacier that feeds the lake. In an advancing glacier, the glacier tongue is so steep that many cracks develop and ice avalanches are easily produced. Ice avalanches falling into the lake will create waves of huge surging pressure to the dam wall. On the other hand, when a glacier extends down into the lake along a gentle slope, ice sliding into the lake creates small pressures to the dam wall. The areas of the glaciers above the end-moraine lakes are usually between 1.5 and 5.5 km² and the glaciers are between 1 and 4 km long. The glacier tongue is generally located in a steep depression or a valley, with the lower part in an

Table 5. Comparison of dangerous and stable moraine-dammed lakes in the Himalaya

	Lake altitude	Lake area	distance to glacier	Glacier terminus elevation	Glacier length	Glacier area	average slope
	m a.s.l.	km²	m	m a.s.l.	km	km²	%
Dangerous							
Jinco	5350	0.550	0	5350	3.8	3.24	34.4
Coxar	5420	0.660	0	5440	2.8	3.43	23.6
Ahamachimaico	5470	0.565	0	5200	3.8	1.66	15.7
Paquco	5300	0.506	0	5320	4.0	5.4	17.8
Stable							
Dongyico	4980	0.040	600	5800	3.1	5.25	18.5
Zongbuxan No. 13	5320	0.198	0	5360	12.5	24.39	7.2
Kada No. 13	5570	0.191	300	5460	8.0	14.49	11.0
Zongbuxan No. 2	5670	0.072	300	5750	5.0	4.96	5.1

extended state, so that cracks tend to form. Thus, it is important to understand recent developmental and morphological features of the glacier to determine whether an end moraine-dammed lake is of potential danger. Table 5 shows some typical end moraine-dammed lakes in the middle Himalaya of China. It can be seen that the potentially dangerous lakes have a larger lake area and a smaller glacier area, a shorter distance from the glacier terminus to the lake and a steeper angle of slope to the glacier tongue than the stable, non-dangerous lakes.

LONG-TERM CHANGES IN FREQUENCY OF OUTBURSTS FROM GLACIER-DAMMED LAKES IN CHINA

Liu (1980) presented results on changes of climate and glaciers in the Karakoram region based on tree-ring statistics (Fig. 3, lower part). Three cold periods (C1, C2, C3) since 1740 correspond to periods of glacier advance (A1, A2, A3). Plotting the number of outbursts from lakes dammed by end moraines in China and the recorded and investigated outbursts from glacier-dammed lakes in the Karakoram mountains, we find that periods of frequent outbursts from glacier-dammed lakes are identical with periods of glacier advance (Fig. 3). Figure 3 shows the total number of outbursts from glacier-dammed lakes in the Karakoram over a period of ten years, as reported by Hewitt (1982) and by the hydrological station, for the southern and northern slopes, respectively. There have been 71 reported outbursts from glacier-dammed lakes in the Karakoram region from the beginning of the 19th century to the present. The periods when outbursts from glacier-dammed lakes occurred most frequently were 1830–50, 1890–1920 and 1960–80, which correspond to periods of glacier advance in 1820–70 (A1), 1880–1930 (A2) and 1950–90 (A3), respectively. This indicates that colder periods give rise to periods of glacier advance, which, after the response time-lag imposed by the glacier dynamics, cause an increase in the number of glacier dams and hence an increase in the number of outburst floods. For the ice-dammed lakes of Iceland, Thorarinsson (1939) came to a similar conclusion. It can also be shown that outbursts from glacier-dammed lakes occur frequently for about 20 to 30 years and with intervals between this activity of about 40 years. Therefore, if glacier advances take place at the beginning of the next century, in response to the cold period since 1940, frequent outbursts from glacier lakes may be expected.

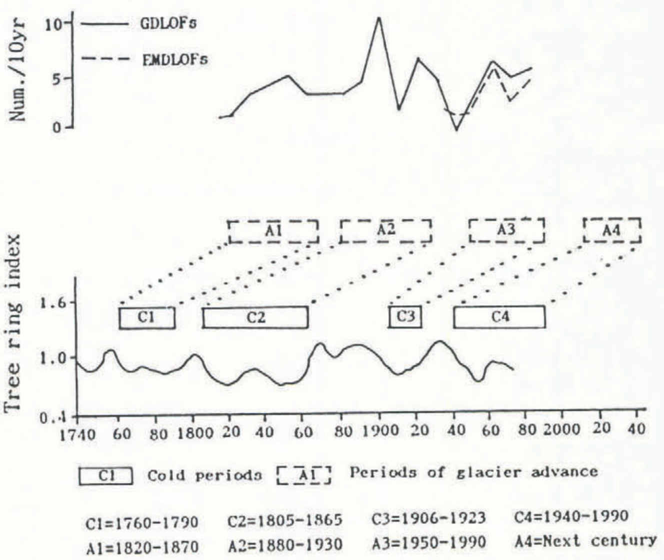

Fig. 3. Comparison between changes in climate, glacier advance and occurrence of outbursts from glacier-dammed lakes (GDLOFs) and from lakes dammed by end moraines (EMDLOFs).

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https://doi.org/10.3189/1992AoG16-1-180-184 Published online by Cambridge University Press