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Article

Dangerous glacier lakes and their outburst features in the Tibetan Himalayas

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Abstract

Field investigation and inventory in the middle section of the Tibetan Himalayas show that the moraine dammed lakes account for 1/2 in number and 3/4 in water volume of all the three types of glacier lakes : the cirque lakes, the trough lakes and the moraine dammed lakes. Thirty-four moraine dammed lakes, with an average water volume of $10 \sim 30 \times 10^6$ m^3, an average depth of 31 m and a field surveyed maximum depth of 71.5 m, are identified with "dangerous glacier lake". Dangerous glacier lakes exhibit the well closed basins with high and narrow moraine ridges and keep connection with the present glaciers, which marks a potential outburst danger. The major triggers of the outburst are (i) ice avalanche from advanced glacier tongue with a volume usually at millions of cubic meters and (ii) ablation activities of dead ice beneath moraine ridges.

1. A brief on study of glacier lake outbursts in the Tibetan Himalayas

In the last fifty years, at least twenty catastrophic outburst events are well known in the Tibetan Himalayas. Outburst floods with rich debris affected hundreds of kilometers downstream and destroyed large amounts of villages, farmlands, forests, water conservancies and communication and transportation installations.

Part of historical outburst data was offered by the interior reports of Comprehensive Scientific Investigation to Qinghai-Xizang (Tibet) Plateau conducted from 1973 to 1976. Yang Zonghui described some recent outburst events (Yang, 1982). The authors made an investigation on the 1981 outburst event along the Boqu (upper Bhote-Kosi) River valley in 1984 (Xu, 1988).

A special investigation on glacier lake outburst floods on the southern slope of Himalayas was made by Water and Energy Commission Secretariat of Nepal (WECS, 1987), in which five outburst events since 1977 were described. Study reports from both the southern and northern flanks of Himalayas showed that all the outbursts were from moraine dammed lakes and most of them led to debris flow.

At present, the government of Nepal is carrying out a water and energy development project. A series of power stations and subsidiary installations will be built in six river valleys, which connect with the Tibetan Himalayas in China, and so the first Sino-Nepalese Joint Investigation to the middle part of the Tibetan Himalayas was carried out in 1987 (LIGG and WECS, 1988). The main subjects of this investigation were inventory and classification of glaciers and glacier lakes, identification of dangerous ones and estimation of the scales of outburst floods and their propagation downstream. The present paper is based on this joint investigation.

2. Types of glacier lakes

Thousands of glacier lakes, distributed around the terminal belts of glaciers at elevations of 4600 ~5200 m, with areas ranging from 2 km^2 to 0.01 km^2, may be divided into three types : glacier cirque lakes, glacier trough lakes and moraine dammed lakes. The statistical characteristics are given in Table 1. The moraine dammed lakes make up 1/2 in number and 3/4 in water volume of all the three types of glacier lakes.

Thirty-four moraine dammed lakes (Fig. 1) mak-

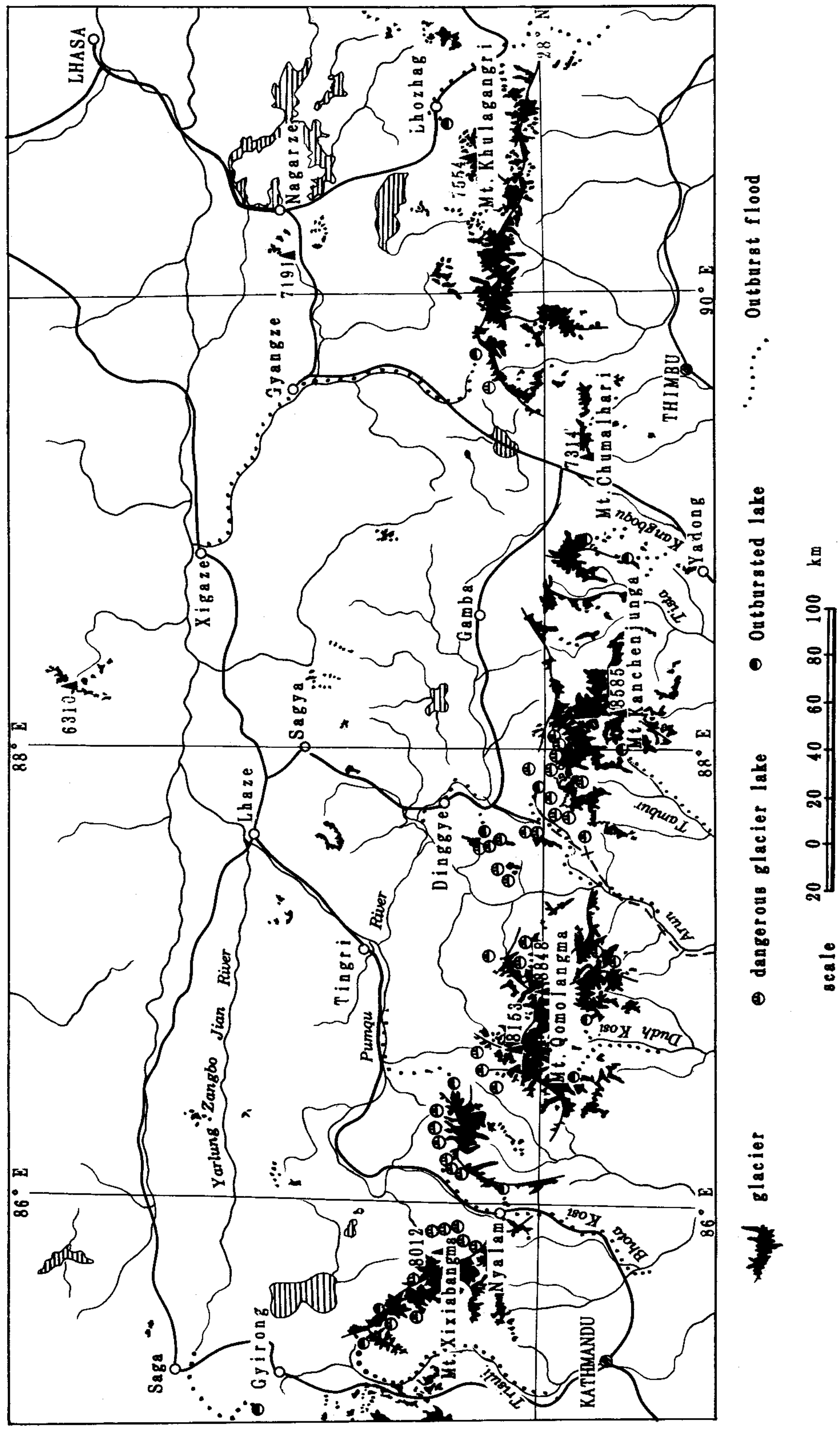

Fig. 1. Map showing distribution of dangerous glacier lake in the central section of the Tibetan Himalayas.

Table 1. Statistical characteristics of glacier lakes in the Tibetan Himalayas.

Lake type	Number		Lake area (km^2)		Water volume (10^6m^3)		Average lake area (km^2)	Average lake volume (10^6m^3)	Average lake depth (m)
	Total	%	Total	%	Total	%			
Cirque lake	86	31.6	5.56	16.7	66	4.4	0.076	0.77	10.1
Trough lake	47	17.3	12.47	22.2	312	20.8	0.265	6.63	25.0
Moraine dammed lake	139	51.1	37.09	66.1	1124	74.9	0.267	8.09	30.3
Amount	272	100.0	56.11	100	1502	100	0.206	5.52	26.8

Table 2. Comparision of dangerous moraine dammed lakes with safe.

Moraine dammed lake	Number	Percentage (%)	Total lake area (km^2)	Total lake volume (10^6m^3)	Average lake area (km^2)	Average lake volume (10^6m^3)	Average lake depth (m)
Dangerous	34	24	18.71	58.4	0.55	17.18	31.24
Safe	105	76	18.38	54.0	0.18	5.14	28.56
Amount	139	100	37.09	112.4	0.27	8.09	29.96

ing up 1/4 of total of this type lakes were identified as dangerous glacier lakes, of which the assessment was judged with morphological analogy of historical outburst lakes, connection with glacier and estimation of water accumulation in lakes. A comparison of dangerous glacier lakes with safe is shown in Table 2, overall, the dangerous glacier lakes have the larger water volume and depth than safe ones.

3. Formation and morphology of dangerous glacier lakes

Below terminals of modern glaciers in the Tibetan Himalayas, there are moraine belts 2~7 km wide with several groups of end moraine ridges representing different stages of glacier expansion during Little-Ice-Age. The group of end moraine ridges nearest to modern glacier is considered as the last stage, which chronologically continued until the middle-late of the last century (Zheng and Shi, 1975). Most of the dangerous glacier lakes occupy the basins formed in the last stage as shown in Fig. 2 though moraine dammed lakes are located widely at the basins formed in various stages. The later the stage is, the greater the moraine ridges are.

The moraine ridge groups of the last stage are usually located within 0.8~1.5 km and up to 2.6 km from modern glaciers. They exhibit fine arched end moraines with heights of 60~120 m and very steep lateral moraines with increasing heights from 60~120 m at the lower end to 150~250 m at the upper end. Dead ices from the past glaciers are scattered widely in the moraine ridges.

The morphological indicators to identify the dangerous glacier lakes may be obtained from the comparison of the present lakes with historical outbursted lakes. A combining indicator is recommended, it is composed of three morphological factors : the height of end moraine dam higher than 60 m, the width of dam top narrower than 50 m and the backside slope of the dam more than 23°. The morphological features of some typical dangerous glacier lakes are listed in Table 3.

4. Outburst features of moraine dammed lakes

During the Sino-Nepalese Joint Investigation in 1987, many dangerous glacier lakes showed a full water stage and the lake water overflowed on a moraine dam, but an ordinary overflow only eroded the dam weakly. The fact shows that the failure of a moraine dam composed of boulder and big stones happens perhaps under an extraordinary overflow and certain conditions though, generally speaking, the newer moraine dams are depositionally loose. Historical events and field surveys show that the main trigger for dam break is ice avalanche, which leads to an extraordinary overflow, and ablation of dead ice in a dam. Ice avalanche from glacier tongue happened usually in an advancing stage of glacier and reached volums of $5 \sim 7 \times 10^6$ m^3, corresponding to 1/4~1/2 of lake volumes.

After the outburst of Gelhapu-Cho Lake in 1964, a big trench appears across the saddles of side ridges right to the moraine dam (Fig. 3). The saddle (5319.6 m, a. s. l.) is about 8 m over the highest level (5311.

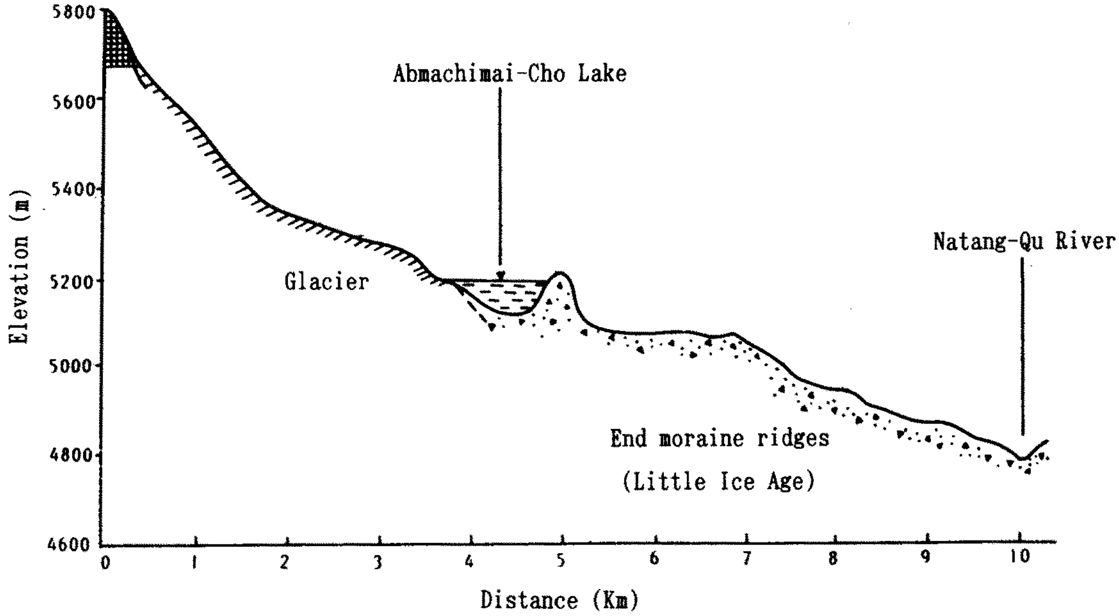

Fig. 2. Longitudinal profile of geomorphology located at the head of Natang-Qu River, a tributary of Pumqu (Upper Arun) River, showing different stages of moraine ridges and the last stage moraine dammed lake.

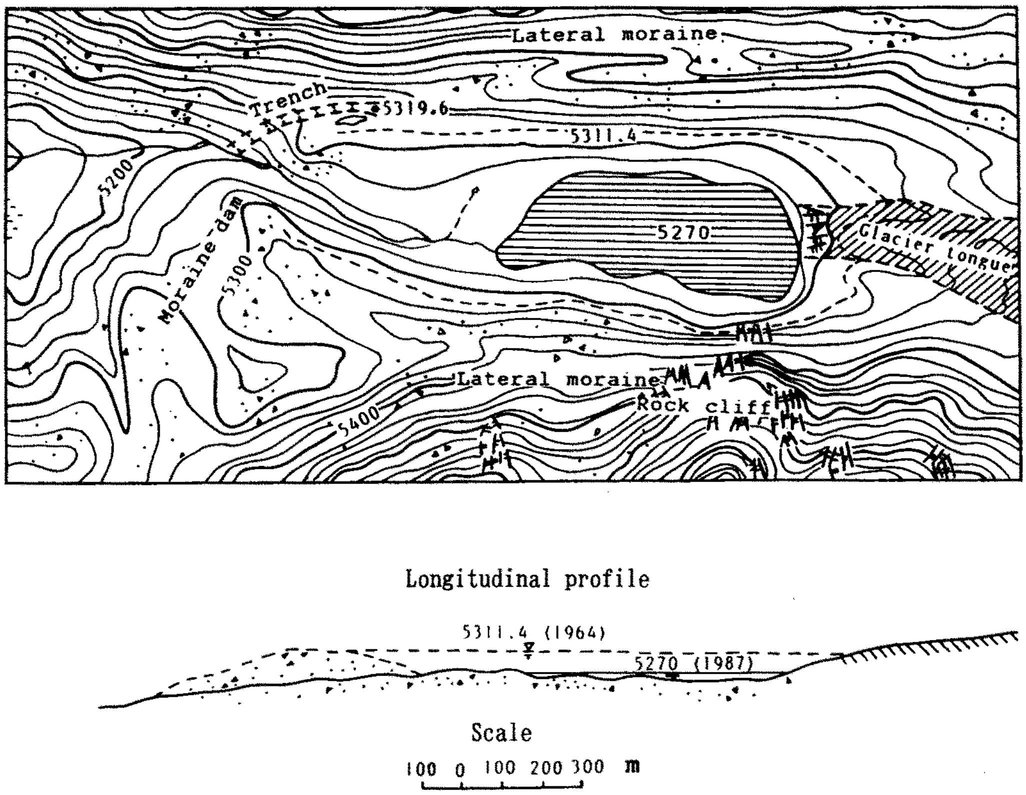

Fig. 3. Topographic map in the area of Gelhaipu-Cho Lake after the 1964 outburst.

Table 3. Morphological features of typical dangerous glacier lakes.

Lake name	Geographic coordinate	Catchment area Total (km²)	Catchment area Glacier (km²)	Lake morphology Altitude (m asl)	Area (km²)	Volume (10^6m³)	Depth Max (m)	Depth Mean (m)	Moraine-dam morphology Height (m)	Width of top (m)	Backside slope (°)
Abmachimai -Cho	28°06′N 87°38′E	7.47	1.66	5200	0.57	19.4	71.5	34	100	20	31.5
Quangzongk -Cho	27°56′N 87°46′E	21.34	11.22	5004	0.76	21.7	69.0	29	80	30	32.5
Gelhaipu -Cho	27°58′N 87°49′E	20.10	8.53	5311	0.58	25.5	71.0	42	120	40	26.8
Paqu-Cho	28°18′N 86°09′E	10.02	7.21	5237	0.51	7.5	45.0	15	80	30	23.0
Lake No. 14	28°07′N 85°54′E	26.80	15.60	5100	1.68	50.5	—	30	80	45	25.0
Zhangzangbu -Cho	28°05′N 86°04′E	5.14	2.83	4700	0.64	18.9	68.0	28	80	40	28.2

4 m a. s. l.) of the lake, the surging flow caused by the large avalanche must once rise up about 8 m from the highest lake level. After the Zhanzangbu-Cho Lake outburst in 1981, the dam-broken lake was filled with huge ice blocks, which were also transported into downstream valley with debrisflood. This ice avalanche was estimated at a volume of 6.8×10^6 m³ from topographic surveying in the area of glacier tongue comparing with air photo taken in 1976. Ice avalanche with such a huge volume must result in a strong surge impact on moraine dam.

Dead ice appears in lens-like bodies and sometimes layers beneath end and lateral moraines. A layer of dead ice with karst features was seen at the bottom of the breached wall of the moraine dam in Zhangzangbu-Cho Lake during author's investigation in 1984 (Xu, 1988). Local herdsmen witnessed piping and sinking of the dam. Piping flow with debris increased rapidly during the last fifteen days before the outburst, which may be one of the causes of this catastrophic event. The cases of piping and sinking of moraine dam due to ablation of dead ice were also observed in Cordillera Blanca in Peru (Lliboutry, 1977). Ice avalanche of glacier and ablation of dead ice happened usually under conditions of strong ablation due to high temperature. Over fifteen outburst events in the Tibetan Himalayas took place in the evening or midnight from July to September as listed in Table 4.

The outbursts must be very rapid as they always make a large outburst breach on moraine dams and a vigorously spreading outburst flood far downstream. The depth of breach usually reaches more than 1/3 of the height of moraine dams with an area of flow cross-section at 2,000～4,000 m² and up to 7,800 m² (Table 4). Assumed that the dam fails instantaneously, the maximum discharge of an outburst flood may reaches 10,000～16,000 m^3s^{-1} at the breach (Xu, 1988 ; WECS, 1987). The extraordinary flood with rich debris endangers hundreds of kilometers of downstream valley.

5. The periodical feature of glacier advance and water accumulation in lakes

The emergence of a glacier lake outburst is conditioned by both the accumulated water as an essential factor and the ice avalanche as a trigger. There seems a synchronous correlation between water accumulation and glacier advance, which favours the outburst occurrence. When a glacier is in an advancing stage, it has a steep and high ice tongue with developed open crevasses. In the strong ablation season, the melt water lubricates the ice bed and a large avalanche is possible to occur, especially in case that the glacier tongue runs into a lake. Thus the outbursts have a close relation with the glacier advance. Figure 4 shows the relation between outburst events and the climatic condition in the Tibetan Himalayas. The outburst events (1964, 1970−1972, 1981−1982 and 1988 in Fig. 4) coincide roughly to the ten or nine year periodicity of climatic variation in temperature and precipitation, and generally tend to the warm years, in which, glacier advincing, glacier surging and ice avalanches were widely recorded in South Tibet (Li *et al.*, 1986).

As an essential factor mentioned above, the outburst can only happen in those lakes in which the

Table 4. Characteristics of glacier lake outbursts in the Tibetan Himalayas.

No.	Outburst lake (Outburst date)	Geo-coordinate (Locate basin)	Lake elevation (m a. s. l)	Lake area after burst (km^2)	Release of water volume ($10^6 m^3$)	Height of dam (m)	Depth of breach (m)	Mean width of breach (m)
1	Tara-Cho 8. 1935	28°17′N/86°08′E Boqu-Bhote Kosi	5240	0.22	6.3	50	10	—
2	Qunbixiama-Cho 10. 7. 1940	27°51′N/88°55′E Kangboqu-Ahmchu	4660	0.21	12.4	—	50	—
3	Sangwang-Cho 10. 7. 1954	28°16′N/90°04′E Nianchu River	5250	7.90	300.0	—	40	—
4	Longda-Cho 25. 8. 1964	28°38′N/85°23′E Gyirong-Trisuli	5460	0.44	10.8	60	22	85
5	Gelhaipu-Cho 21. 9. 1964	27°58′N/87°49′E Pumqu-Arun	5271	0.14	23.4	120	41	205
6	Damenlahe-Cho 26. 9. 1964	29°50′N/93°09′E Nyang River	5210	0.09	2.0	35	17	85
7	Aya-Cho 18. 8. 1970	28°21′N/86°30′E Pumqu-Arun	4920	0.35	90.0	70	20	160
8	Poge-Cho 23. 7. 1972	28°19′N/90°41′E Xibaxiaqu	4330	—	—	—	8	—
9	Zari-Cho 24. 6. 1981	28°59′N/85°09′E Yarlung Zangbo	—	—	—	—	—	—
10	ZhangzangbuCho 11. 7. 1981	28°05′N/86°04′E Boqu-Bhote Kosi	4700	0.31	18.9	80	32	145
11	Jin-Cho 27. 8. 1982	28°12′N/87°38′E Pumqu-Arun	5350	0.55	12.8	60	25	130
12	Mitui-Cho 14. 7. 1988	29°30′N/96°17′E Palong Zangbo	3815	0.09	3.3	45	17	22

Note :

1. Dam piping. Debris-flood buried farmlands at the mouth of the tributary valley.
2. Ice avalanche. Debris-flood washed Yadong at 50 km from the lake, with a peak discharge of 1,200 m^3s^{-1}.
3. Glacier advancing into lake, ice avalanche. Debris buried up valley 3-5 m thick and flood damaged the cities of Gyangze 120 km away, with a peak discharge of 10,000 m^3s^{-1}, and Xigaze 200 km away from the lake.
4. Debris-flood with a peak discharge of 3,100 m^3s^{-1} blocked Gyirong (up Trisuli) River.
5. Ice avalanche. Debris-flood with a peak discharge of 3,260 m^3s^{-1} at 30 km from the lake.
6. Ice avalanche with a volume of 5×10^6 m^3. Debris flood dammed up forming a debris dam 20 m high and 850 m long at the confluence with Nyang River and stopped the river for 10 hours.
7. Debris-flood formed a new debris fan of 4.6×10^6 m^3 near Tingri at 40 km from the lake.
8. Ice avalanche with a volume of 5.7×10^6 m^3. Flood hazard far spreaded.
9. Ice avalanche. Debris-flood destroyed all the local economic constructions in the upper valley.
10. Ice avalanche with a volume of 6.8×10^6 m^3. Debris flood destroyed the China-Nepal Highway and all the structures within 50 km in the upper valley.
11. Ice avalanche. Debris-flood destroyed eight herdsmen villages and killed 1600 livestocks.
12. Ice avalanche with a volume of about 3×10^6 m^3. Debris-flood with a maximum discharge at about 1,540 m^3s^{-1} destroyed a highway 30 km long and two villages in the upper valley and caused several people's death.

Table 5. Field measured discharge of leakage through moraine dam.

Lake	Water store	Leakage discharge (m^3s^{-1})	Measurement	Duration
Abamachimai-Cho	Full stage	0.112	Runoff separation	02～20May 1987
Qangzongk-Cho	Full stage	0.128	Direct measure	08May 1987
Zhangzangbu-Cho	Low stage	0.268	Direct measure	21～23 Sep. 1984

water accumulation is able to reach an approximate full stage. Water accumulation depends on the water balance in lake. At present, limited by data, only a rough estimation can be given. The overflow may be ignored as the water balance here is under "full water stage". Thus the way of normal release is leakage through moraine dam and evaporation. The leakage flow measured is 0.112～0.268 m^3s^{-1} as shown in Table

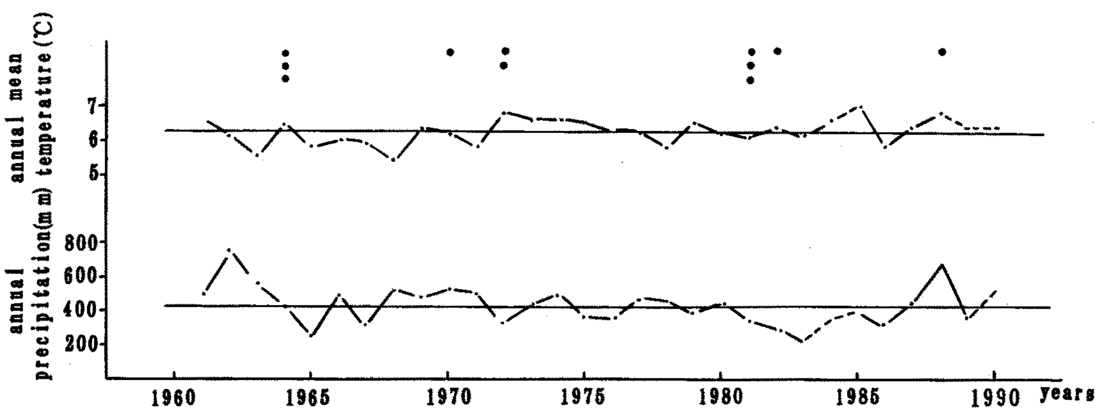

Fig. 4. Relation of outburst events with climate change by Xigaze Climate Station.

5, corresponding to a yearly loss of water volume at 3. $5\sim8.5\times10^6$ m^3. Based on the evaporation data obtained at Tingri and Nyalam Climate Stations, the lake surface evaporation is between 350 mm and 600 mm from June to November, which corresponds to a yearly loss of water volume of $0.18\sim0.3\times10^6$ m^3 or 0. 24×10^6 m^3 in average as for lakes with an area about 0.5 km^2. Therefore, the outflow sums up to 3.74~8. 74×10^6 m^3.

The lake water is mainly supplied by glacier melt water and precipitation in the catchment above dam during the melting season. Based on data observed in the catchment (above 5027 m a. s. l.) of the Rongbu Glacier on the northern slope of Mt. Everest, the glacier ablation and precipitation are 530 mm and 205 mm respectively and make up 66.4 % and 25.7 % of total annual supply (Xie, 1975). Thus the inflow to the lake is estimated at $2.5\sim12.0\times10^6$ m^3 for those lakes with drainage areas of 5~26 km^2 and glacier area ratioes of 0.22~0.72, shown in Table 3. The above estimation implies that those lakes keep an equilibrium between inflow and outflow in general and they are able to store the water up to a full stage in the periodically warm years just as many overflowing lakes were seen during the 1987 joint investigation.

Water accumulation in lake is also characteristic of a periodicity following climate change. It is evident that the area of lakes increased largely and glaciers advanced visibly in many areas of the Tibetan Himalayas in 1987 in comparision with 1976 air photo or 1984 investigation. The area of the Qangzongk-cho Lake had increased from 0.43 km^2 to 0.76 km^2 since 1976. The lake No. 14 had increased in area from 0.83 km^2 to 1.68 km^2 and the water submerged the small dam of a branch glacier and met with it, the main glacier above the lake had extended to 1.6 km^2 down into the lake since 1984.

6. The scale of outburst floods and propagation along downstream valley

The outburst of Zhangzangbu-Cho Lake in 1981 caused a large scale of debris flood spreading 50 km along the Poqu (Bhote-Kosi) River valley. The peak discharge at Bharabise, 50 km from the lake, reached 2,400 m^3s^{-1}, which is 12 times of the maximum of annual discharge. The outburst flood from Sangwang-Cho Lake in 1954 damaged two big towns, Gyangze and Xigaze. At Gyangze about 120 km downstream from the lake, the peak discharge reached 10,000 m^3s^{-1}, which affected the Yarlung Zangbo River 200 km away from the lake with flood washes.

The scale of outburst flood and its downstream propagation is determined mainly by the total volume of released water from the lake and the instantaneous maximum discharge at the breach. The volume of released water ranges greatly but mostly from 10×10^6 m^3 to 20×10^6 m^3 (Referring to Table 4). The maximum discharge at breach and any given downstream site can be obtained by computer simulation with a proper model (WECS, 1987). However, we have not gotten the true conclusion about the course of a moraine dam failure and the ways how to treat debris flow in simulation.

The course of a moraine dam failure may be simplified into two models, erosional succession and instancy. It would be reasonable to adopt a succession model in many other cases, but in case of a huge volume of ice avalanche with high down speed, an instancy model is advisable.

Because of strong down-cutting and backward erosion in source waters, morainic and other weathering materials and slope wasting products fill valley bottom and sides. These unstable loose materials always join to come a debrisflow under conditions of extraordinary floods. During propagation of a debris flood, the flow is rapidly changing with debris, which dams up one moment, disperses the next and sometimes is replenished from flow bed and sides in erosion, sometimes is reduced in deposition. It is difficult to simulate the discharge or stage of a debris flood, but it is very important for hazard forecast and engineering objectives.

Himalayas are the most serious mountain area of outburst hazards in the world. A multitude of dangerous glacier lakes has been threatening the economic development as well as people's life in the area. The water accumulate of lake and glacier advance as seen in the 1987 joint investigation revealed the next forthcoming outburst period and it had appeared in the events afterward such as Mitui-Cho glacier lake outburst (Table 4) and the recurrence of violent glacial debrisflow by ice avalanche in Palong-Zangbu Glacier valley (30°04′N, 94°58′E), the eastern Himalayas, respectively in 1988 and 1989.

Limited by fund, the further work on monitoring of dangerous glacier lakes and control of disaster has not been put on the order of the day in Tibet. The tracking of regime and its trend on "lake-glacier -enviornment" system by means of satellite remotesensing technique with the geographic information system (GIS) would be effective not only to prevent us from a abrupt attack of outburst debris flood, but also to study further on the mechanics of a moraine dammed lake outburst.

Acknowledgments

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