6. Potentially Dangerous Glacier Lakes Evaluated in the Nepal Himalaya

6. 1. Identification of Potentially Dangerous Glacier Lakes

One set of the oblique aerial photographs of the glacier lakes was obtained by means of flight observations. The photographs indicate the surroundings of a lake such as the mother glaciers, moraines and the topographical features around the lakes. Using these photographs the potentially dangerous glacier lakes are identified according to the following criteria (Yamada, 1993) ;

1) Condition of a moraine-dam ,
2) Size of a lake,
3) Topographical features around a lake

Glacier lakes are often dammed by ice-cored moraines. When cored ice gradually melts, the dam decreases in height and becomes significantly weakened. An ice-cored dam is evaluated by inspecting the surface features of the end moraine. This may be easily examined by the existence of many outcrops of bare ice, many ponds formed by the meltwater of the ice body buried in the moraine, as well as traces of ponds previously formed and drained out.

Larger area and larger volume of stored water can cause more serious disaster as already discussed in Section 4. 3. For evaluating the volume, depth measurement of the lake has to be carried out by a field visit. At present only the area of a lake is employed as a rough evaluation criteria to determine whether the lake is hazardous or not.

A glacier lake surrounded by steep slopes has potential risks due to snow, ice and rock avalanches and slope failure. If the glacier has a cliff at the terminus and it contacts with the lake, the glacier calving / falling / sliding will help trigger a dam burst.

Potentially dangerous glacier lakes among the glacier lakes observed are listed below in order from east to west in the Nepal Himalaya. Because no infrastructure and no significant land use bring any damage and give any serious impact, the scale of damage along a GLOF path is also taken into consideration to identify the dangerous lake

1) Glacier lake formed on the Lower Barun glacier (Photo 4 ; No. 4 in Fig. 4)
2) Glacier lake formed on the Imja glacier (Photo 1 ; No. 1 in Fig. 4)
3) Tsho Rolpa of the Trakalding glacier below the Trambau glacier (the cover photo and Photo 14 ; No. 14 in Fig, 5)
4) Glacier lake formed on the Thulagi glacier (Photo 18 ; No. 18 in Fig. 5)

The distribution of the above lakes in the Nepal Himalaya are shown by arrows in Fig. 5. It should be noted that this is not a final list because of an inability to complete a full study of the entire Nepal Himalaya.

6. 2 Outline of the Dangerous Lakes

Among the potentially dangerous glaciers listed above, the investigation had been carried out by a field visit in the Lower Barun glacier lake (Kadota and Mool, 1993), the Imja glacier lake

(Yamada, 1992 ; Watanabe et al., 1994 ; Watanabe et al., 1995), Tsho Rolpa (Mool et al., 1993 ; Kadota, 1994), and the Thulagi glacier lake (Mool et al., 1995). After investigation at the reconnaissance level, more detailed investigations had been carried out in Tsho Rolpa (Yamada, 1996) and Thulagi glacier lake (DHM/FIGNR, 1997).

Outlines of above glacier lakes are tabulated in Table 3 and the bathometric maps of these lakes are shown in Fig. 6. Depths of the lakes were measured in late winter when the lake was still covered with thick ice by means of measuring tape dropped into the lake through the holes opened in the ice cover.

Glacier lakes in the Nepal Himalaya are generally located at altitudes between 4000 m and 5000 m. The depth of the lake is remarkably deep enough to store a huge amount of water of 30 - 80 million m^3 as shown in Fig. 6 and Table 3. It can be clearly seen in the bathometric map of Fig. 6 that the deepest point is not located at the center of the lake but near the glacier terminus, which may be a reflection of the expansion mechanism of the lake.

The lakes are quite young and born within the recent quarter or half century. The approximate age of the lake is estimated by establishing the development processes of each lake by using all the available information such as published maps, terrestrial photographs, aerial photographs and satellite imageries as discussed in the next Section. It is clear that the lakes are still growing year after year.

The above mentioned lakes have similar morphological features. The lakes are all developed on the stagnant glacier tongue covered by thick debris. The uplake end touches the cliff-shaped glacier end. The lakes are dammed by the lateral and end moraines with the exception of the Thulagi glacier lake. The moraine-dams are composed of quite fresh and loose materials with no vegetation cover. It indicates that the moraines have been formed during the Little Ice Age during the 16th-19th centuries as mentioned in Section 3.1.2. The lateral moraines are quite high, assumed to be 70 to 80 m from the lake surface. The end moraines rise approximately 100 - 150 m in height from the valley bed level and clearly contain glacier ice. Lake waters are being drained out through a small outlet on the end moraine throughout a year even in winter. The overflow from the lake is

Table 3 : Outline of the potentially dangerous glacier lakes in the Nepal Himalaya.

Name of the lake	Lower Barun	Imja	Tsho Rolpa	Thulagi
Location	27°48′ N	7°59′ N	27°50′ N	28°30′ N
	87°07′ E	86°56′ E	86°28′ E	84°30′ E
Altitude (m a.s.l.)	4570	5000	4580	4146
Depth (m) Average	47	47.0	55.1	41.8
Maximum	109	99	131	81
Length (km)	1.1	1.3	3.2	2.0
width (km)	0.6	0.5	0.5	0.45
Area (km^2)	0.6	0.60	1.39	0.76
Stored water (million m^3)	28	28.0	76.6	31.8
Drainage area (km^2)	-	-	77.6	55.4
Approx. Age	30	30	45	35
Data obtained in	Mar. '93	April, '92	Feb. '93 & Feb. '94	Mar. '95

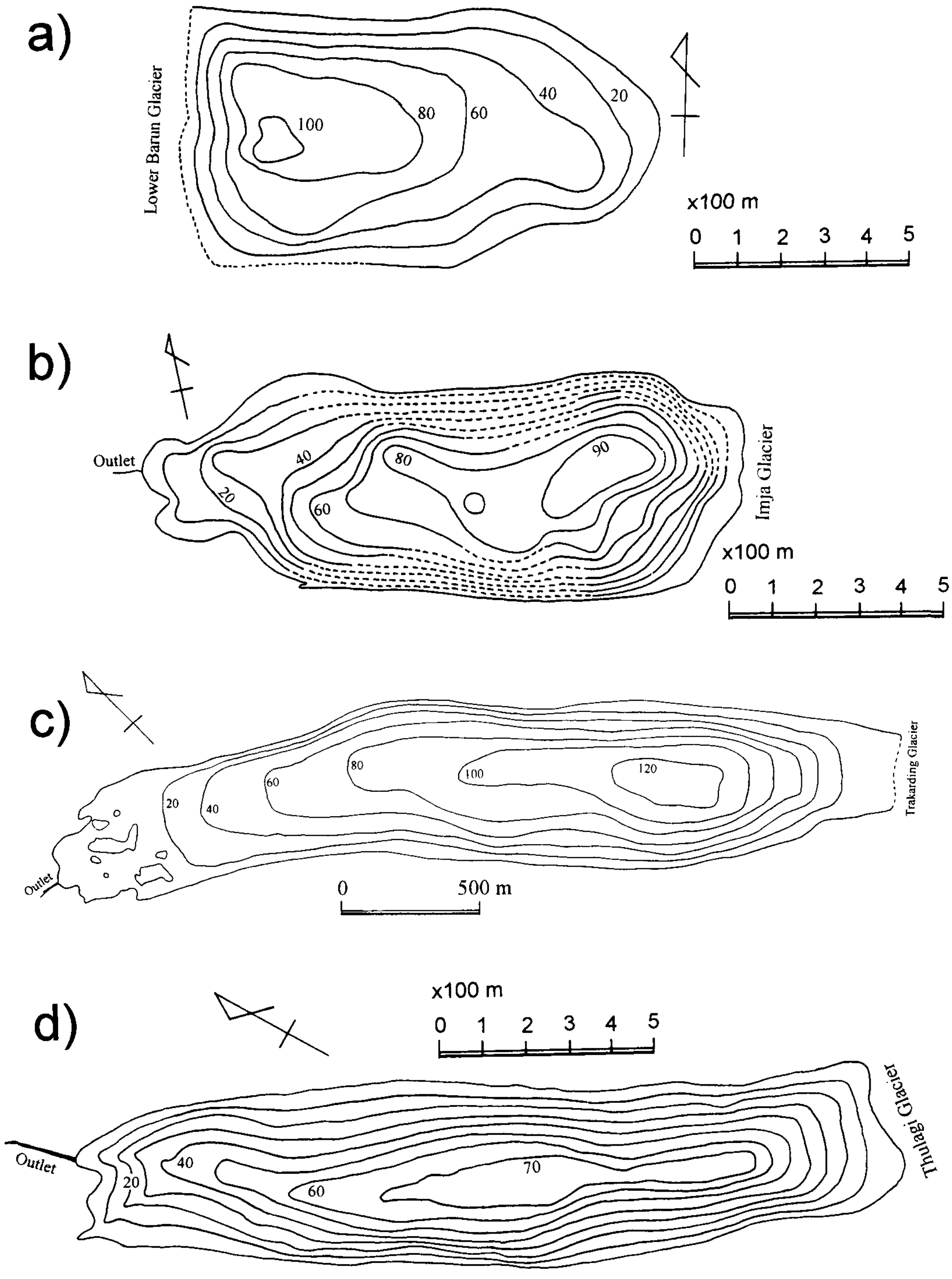

Fig. 6 : Bathometric maps of glacier lakes : a) Lower Barun ; b) Imja ; c) Tsho Rolpa ; d) Thulagi.

supplied from rainwater and meltwater in the drainage basin of the lake. The ridge level of the end moraine is relatively lower than that of the lateral moraine. It is believed to be very rare case that only Thulagi is dammed by dead ice mass covered by debris (DHM/FIGNR, 1997).

6. 3 Development Processes of the Dangerous Lakes

6. 3. 1 Lower Barun Glacier Lake

According to Kadota and Mool (1993), no lake could be identified on the topographical map published in 1967 by Survey of India, which was based on vertical aerial photographs taken in 1958/59. Ponds or a very small lake could be seen on the first edition (1978) of "Schneider Map", Khumbu Himal on a scale of 1 : 50,000 prepared by the field work in 1955-63. A large lake was found on the glacier tongue in the LANDSAT imagery taken in 1976. That the lake is continuously growing after 1976 was noticed with the aid of an Infrared Metric Camera Photo of SPACELAB taken in 1983 and an aerial oblique photograph taken in April, 1991 (Yamada, 1991). A field survey made in February 1993 (Kadota and Mool, 1993) derived the lake area as 0.6 km^2.

As a result of extrapolating this growing trend to the past, it appears that the lake was probably born in the early 1960s. Its age may have been about 30 years by 1993. Debris-covered ice may have melted out at least 109 m at the deepest point probably within 30 years. If melting and the expansion of the lake was started at the deepest point, the average melting rate is evaluated to be at least 3.6 m/year.

The above estimation of the melting rate is probably underestimated due to the following two reasons. (1) The deepest point is not always the initial position at which melting and expanding of the lake begins. If the point started melting recently, the above melting rate is probably underestimated. (2) Since the surface level of the deepest point in the initial stage of lake formation may be higher than the present water level of the lake, so that the total melting depth is more than the maximum lake depth ; the melting rate may actually be larger than the evaluated value.

These under-estimations may be true for the melting rates evaluated in the following three glacier lakes also. If so, the actual melting rates are probably concluded to be remarkably high at the deepest point in the lakes.

6. 3. 2 Imja Glacier Lake

Since the lake is located at the heart of the Nepal Himalaya, many climbers, researchers and workers for mapping visited this area and took terrestrial oblique photographs and also vertical aerial photographs. The development processes of Imja glacier lake was reconstructed by collecting those photographs and maps published (Yamada, 1993 ; Watanabe et al., 1994).

No lake can be seen in the photographs taken in 1956 by Muller (Swiss Everest / Lhotse Expedition of 1956), in 1963 by Bishop and probably in 1971 by Fushimi (Japanese Glaciological Expedition of Nepal, GEN). No lake but a couple of ponds can be found in the well known topographical map as the "Schneider Map", Khumbu Himal (1 : 50,000), which was based on the terrestrial photogrammetry and field works made from 1956 to 1963. The map shows only a couple of small ponds on the glacier tongue with a total area of 0.03 km^2. The lake was first recognized in the terrestrial oblique photographs taken in 1973 by Japanese glaciological research team (GEN). The aerial oblique photographs taken in 1975 and in 1978 by GEN shows the large lake with islands and peninsulas. The size of the lake is respectively estimated to be around 0.30 km^2 in 1975 and 0. 36 km^2 in 1978. The islands and peninsulas disappeared by melting up to that time when the vertical aerial photographs was taken in December 1984 as the basis for the National Geographic Society 1 : 50,000 map. We can see the large lake within an area of 0.47 km^2 on the map published in 1988. According to the result of the field survey made in early April, 1992 (Yamada, 1992), the area of the lake expanded to 0.60 km^2 as seen in Fig. 6-b. The age of the lake as of 1992 may be estimated to be about 30 years old.

The Imja lake having a maximum depth of 99 m has been melted within the last 30 years. The average annual melting rate at the bottom of the lake is estimated to be at least 3.3 m/year.

6. 3. 3 Tsho Rolpa Glacier Lake

The developing history of Tsho Rolpa was intensively reconstructed as shown in Table 4 and Fig. 7 (after Mool et al., 1993 ; both modified). The figure was made on the basis of the maps, such as Survey of India Map(1 inch : 1 mile), Schneider Map of Rolwaling Himal (1 : 50,000) and Nepal / China Boarder Map (1 : 50,000), and satellite imageries. The Table also shows the lake areas surveyed by Mool et al. (1993) in 1993 and Kadota (1994) in 1994.

The lake might be concluded to expand from early 1950s by extrapolation of the relationship between year and area as shown in Fig. 8. The lake age is derived to be about 45 years old in 1994. The average deepening rate in the lake bottom and elongation rate in the longitudinal direction of the lake are respectively evaluated to be at least 2.9 m/year and 71 m /year.

By carefully inspecting Fig. 7, it is concluded that the position of the present deepest point in1993 belonged not to the lake but to the Trakarding glacier in the early 1970s. As the lake was elongated upstream due to calving of the cliff-shaped terminus of the mother glacier, the point was

Table 4 : Lake areas of Tsho Rolpa estimated by means of various data sources.

Source	Year of Survey/Image	Area (km^2)
Vertical aerial photos (for the map by Survey of India)	1957-59	0.23
Schneider Map	1960-68	0.61
ERTS, MSS	14 Dec., 1972	0.62
Nepal / China Boarder map	1974	0.78
LANDSAT, MSS	2 Nov., 1975	0.80
LANDSAT, MSS	20 Mar., 1977	0.80
LANDSAT, MSS	24 Jan., 1979	1.02
SPASELAB METRIC CAMERA, IR	3 Dec., 1983	1.16
LANDSAT, MSS	9 Apr.., 1984	1.16
MOS 1, MESSR	21 Oct., 1988	1.27
MOS 1, MESSR	9 Nov., 1990	1.27
Field survey by WECS	Jun., 1993	1.37
Field survey by Kadota	Jun., 1994	1.39

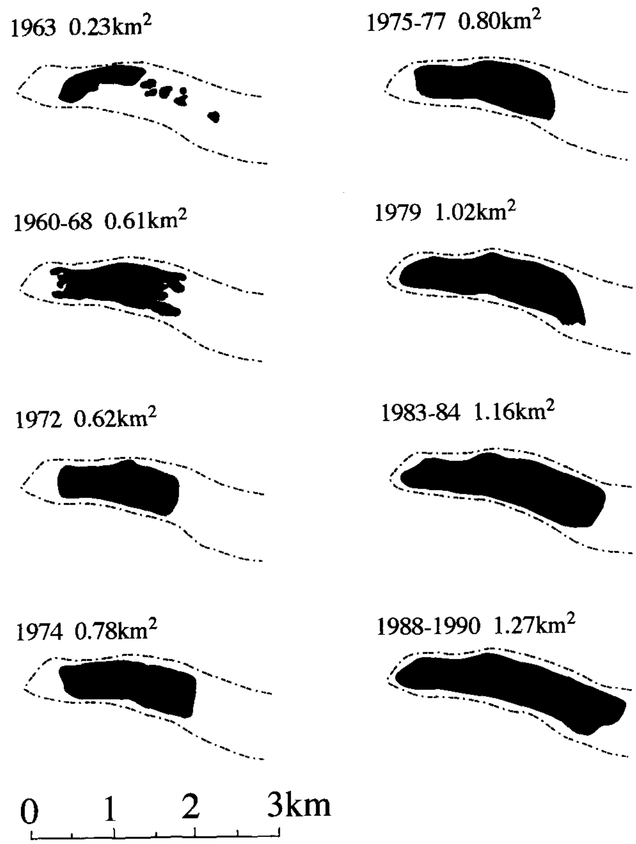

Fig. 7 : Expansion processes of Tsho Rolpa.

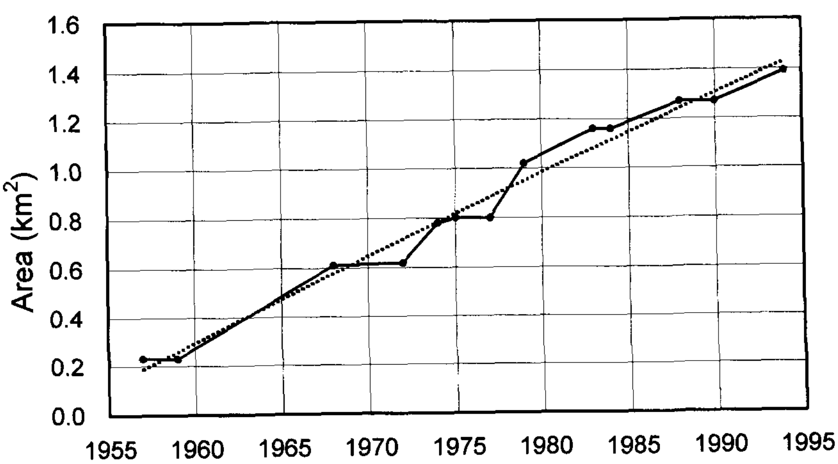

Fig. 8 : Expansion of the lake area with the lapse of time.

involved in the lake and deepened to the maximum depth of 131 m, which had been realized within only a quarter century. The above value of 2.9 m/year should be corrected to be around 5 m/year. As for the above-mentioned two lakes the average melting rate of 3.6 m/year for the Lower Barun glacier lake and 3.3 m/year for the Imja glacier lake, respectively, might be revised to a larger value for the same reason as Tsho Rolpa.

6. 3. 4 Thulagi Glacier Lake

The development processes of Thulagi glacier lake are reported by Mool et al. (1995) on the basis of the field survey made in March, 1995. The paper states *"Comparison to Topographical map 1958 (survey of India) shows that the lake had surface area 0.22 sq. km and length of 600 m but the glacier has retreated by 1400 m for the last 3 decades and now the lake has surface area 0.76 sq. km and the length of 1.97 km and width of 0.45 km. Comparison to existing maps, it is evident that the width of lake has not changed much but the size has increased almost 3.5 times."*

By extrapolating the above information to the past, the age of Thulagi glacier lake was probably estimated to be at least 35 years. The average melting rate is estimated to be 2.3 m/year without any complicated consideration.

6. 3. 5 Conceptual Features of the Development Processes of a Moraine-dammed Glacier Lake

The above-mentioned facts naturally lead to the derivation of a concluding concept of the development processes of a moraine-dammed glacier lake as schematically illustrated in Fig. 9.

Before a glacier lake is born, only small ponds exist on the debris-covered glacier tongue as shown in Fig. 9-a. These kinds of ponds are usually seen on the debris-covered glaciers in the Nepal Himalaya, for example, on the Lhotse glacier, the Khumbu glacier and the Ngozumpa glacier in the Khumbu Himal, and the Langtang glacier in the Langtang Himal. Nobody knows when the ponds begin expanding to a lake or not.

By exceeding some unknown critical condition for melting, the ponds start expanding to become a lake by interconnection with each other accompanied by further deepening so that a moraine-dammed lake is born (Fig. 9-b). Photo 15 seems to be a typical and better example for this initial stage of the lake formation. At this stage it may be difficult to identify whether the water storage is still a pond / ponds or has already become a lake because there is no clear dividing line between a pond and a lake.

Continuing this melting trend, the lake expands into a rather large size in terms of area and depth. The terminus of the mother glacier contacting with the lake may become a cliff. A continuous melting of glacier ice beneath the lake bottom and a continuous calving of the cliff-shaped glacier terminus result in the further expansion of the lake. Some point of the lake may reach to the maximum depth due to glacier ice beneath the lake melting away to the bedrock (Fig. 9-c).

The lake would finalize its development process and would reach its maximum size when the lake level becomes equal to the grounding level of the mother glacier (Fig. 9-d). After that, the lake would separate from the mother glacier with no further development. This is the final stage of lake

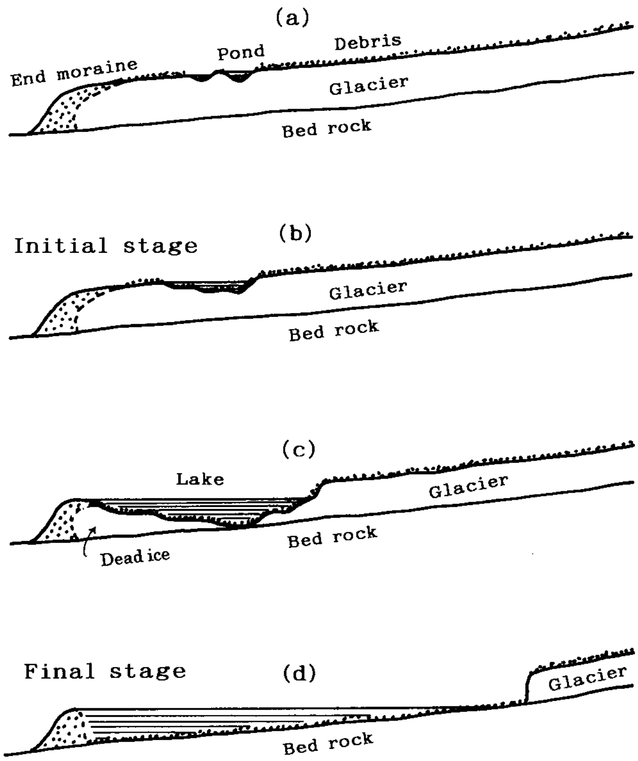

Fig. 9 : Conceptual illustration of the development of a moraine-dammed glacier lake. Dots on the glacier surface and the dotted area at the glacier terminus indicating debris on the glacier and the end moraine, respectively.

development. The dead ice in the moraine and beneath the lake bottom would then ultimately disappear.

Four lakes treated above are still in the developing stage between the initial stage and the final stage. They will eventually reach the final stage and grow to maximum size if the moraine-dams never burst. This concept of lake development can be adapted to any other moraine-dammed lake.

Though numerous debris-covered glaciers are found in the Nepal Himalaya, the glaciers do not always have a glacier lake. Even in the same glacierized region, some particular glacier has a glacier lake while others do not in spite of those glaciers being located in the same climatic condition. For instance Imja glacier has a glacier lake but Lhotse glacier has no lake but only small ponds.

Melting rate of debris-covered glacier is considerably low because of heat insulation effects of thick debris. Debris surface is heated up by solar radiation achieving high temperature. On the other hand, the surface of ice body under the debris is kept at freezing point. The heat source for ice melting is only from conductive heat due to the vertical temperature gradient in the debris, though, in the case of a bare glacier surface, heat sources such as latent / sensible heat and solar radiation work directly to melt ice.

Once a supra-glacial pond is created on the glacier, surface heat balance may change drastically as discussed in Section 7. 8. Convective heat transfer starts to work. Conduction is not as efficient as convection to effectively transfer the heat from the surface to the bottom. Positive feed-back mechanism may be expected for a lake formation, that is, once depth of a pond exceeds a critical value and lasts long enough, melting rate may be accelerated for effective heat transformation into the glacier ice beneath the pond bottom. The pond starts to expand, which may prepare more effective condition for bottom ice melting. If the above discussion is right, other lake-free glaciers have a chance to form a lake corresponding to the progressive global warming.

Existence of water with free surface on the glacier drastically changes the thermal condition of the glacier surface with the result that it can absorb more heat than that on the debris covered area of a glacier. Usually a pond is not stable : The existing pond is occasionally emptied owing to the englacial channels beneath the ponds possibly created by ice melting as stated in Section 7. 8 ; a new pond is casually created on the depression part during the melting process of a glacier. It may be essential for a lake formation that a pond should lasts long enough at the same position on the glacier. What critical conditions is required for the lake development ? It is strongly need for the prediction of future glacier lake formation in the Himalayas that the question should be solved by the future studies. It should intensively studied to find out the critical condition in the development of a lake from ponds.

Permafrost (permanently frozen ground) develops in the Great Himalayan regions because of the sub-polar climate conditions. According to Fujii (1980), who investigated the distribution of permafrost in the Khumbu region, it was distributed in the area above 4,900-5,000 m a.s.l. Therefore moraine-dams located above this level are frozen. Recent global warming tends to weaken frozen moraine-dams due to the acceleration of melting both the frozen moraine and the ice cored in the moraine. Further studies on the frozen condition of a moraine-dam are desirable.

Why is a lake formed only in a particular glacier among glaciers in the same climatic condition ? Why has the lake developed so quickly as discussed above ? Furthermore, why are there very few records of GLOF before the 1960's as listed in Table 2 ? To give the proper answer to these questions, intensive investigations had been conducted at Tsho Rolpa glacier lake from 1993 to 1996. The provisional results of the Tsho Rolpa studies will be presented in the next Chapter. Analytical results and detailed discussions has been and will be published on the scientific journals.