8. Possible Countermeasures against GLOF Disaster

It is strongly recommended that planners and engineers involved in water resources development and the construction of infrastructure in the vicinity of glacier areas have to pay careful attention to GLOF not only in Nepal but also other Hindu Kush - Himalayan countries. To avoid unexpected GLOF disaster is one of their concerns. They have to first carry out careful observation of potentially dangerous glacier lakes in the upper watersheds of the operation site by means of satellite imageries and flight observations. Next, they have to visit the lakes to estimate the volume of stored water in the lakes and to obtain the overall information of the moraine-dam condition and physical condition of the lake such as meteorological, hydrological condition etc. Computer simulation should be made by potential flood wave analysis i. e. the maximum discharge and the peak level of flood water along the river channel in possible cases of initial amounts of discharge released from the lake. Then, the hazard map should be prepared. Finally the best countermeasures should be selected.

Countermeasures against GLOF disaster are divided into two categories (i) prevention of a lake burst and (ii) mitigation of a flood impact downstream.

8. 1 Prevention of Lake Burst

In order to effect civil engineering intervention at the glacier lake directed at preventing the lake-burst, the following possible countermeasures are presented :

1) to render the moraine-dam strong enough to resist failure due to overtopping of the lake water : for example, cementing by concrete milk, gabion wall and/or other proper methods, and
2) to decrease the volume of stored water in the lake to a safe level ; first by lowering the lake level and then by excavating a tunnel or deepening the breach of the moraine-dam to retain the lowered level.
3) the lake level can be lowered by :
   a. siphon system,
   b. electrical pumping operated by electricity generated *in situ* from the water mass flowing down from the glacier lake, and
   c. controlled blasting of the moraine-dam by means of explosives.

Since a glacier lake usually stores a huge amount of water, if the technology to strengthen a moraine-dam could once be developed, a glacier lake would become a good and economic natural reservoir. The controlled lake water could be utilized for hydro-electricity generation and other uses as a sustainable water resource. To strengthen the moraine-dam would be technically difficult because of instability of a moraine consisting of loose materials.

Lake water reduction by draining out is the most drastic, essential and the only possible countermeasure for the prevention of a lake-burst for eliminating the cause of flood. After having achieved lowering of the lake level, a proper spillway should be constructed on / in the moraine

-dam to obviate the recovery or rebound of the water level. Spillway construction on / in the moraine is likely to demand more or less laborious work because of the difficulty in employing heavy duty construction machines but it may be worthwhile to examine the option. The glacier lakes are located in remote areas of extreme altitude with sub-polar climate in the deep Himalaya. There are no roads and airport facilities to transport heavy equipment, machinery and construction materials, and also no commercial electricity. Airborne operation may be done to a limited extent through the use of helicopters ; air transportation of heavy loads would be constrained owing to the high altitudes. The "low-technology" approach adaptable to the harsh site conditions should be developed before the commencement of any construction work.

It is noted that before making a spillway on the moraine-dam, the existence of the dead ice body buried in the moraine should be confirmed by means of physical explorations such as electrical resistivity survey, electro-magnetic survey, seismic survey and / or other proper methods. If dead ice is once exposed, severe melting, maybe more or less 5 m of ice melting, will immediately occur during a summer season. It will quickly weaken the moraine-dam thereby destroying it spontaneously in the process.

Among the methods for lowering the water level mentioned above, the method A would be believed to be the most practically acceptable technique offsetting the need for electric power supply, heavy duty machines and construction materials. Adopting an electric pumping system (the method B) appears to be an attractive proposition worthy of careful examination although acceptability would depend on its cost effectiveness. In the case of Tsho Rolpa, the height of the end moraine is 150 m and the annual volume discharged from the lake is estimated as 10^9 m^3, where more than 1 m^3/s of discharge is expected during the 5 months from mid-May to mid-October (Yamada, 1996). Water energy of 1 m^3/s with a head of 150 m is estimated to be able to generate about 750 kWh of electricity at an assumed efficiency of 50 %. The method C is too risky because controlling the high energy of the rushing water drained out from the lake seems to be technically difficult ; the moraine-dam may be spontaneously destroyed and GLOF may occur artificially.

8. 2 Mitigation of GLOF Impact

Once GLOF happens, nobody can stop its huge energy. This is a case of implementing countermeasures against GLOF downstream of a glacier lake without direct engineering intervention to the lake itself. This mode aims not to prevent the lake burst but to mitigate the GLOF hazard. The possible countermeasures are :

1) preparation of a hazard map and the estimation of the possible hydrograph along the river channel downstream using proper simulation models to predict and to understand the kind of probable damage to be expected when GLOF happens,
2) installation of a monitoring and warning system to detect the signal of the lake burst and to propagate this information immediately to the place likely to be affected, which should work on a 24 hour operational basis,
3) construction of several trapping dams with enough capacity to capture the debris and to dissipate the GLOF impact,

4) replacing the infrastructures to the places of safety,
5) strengthening the infrastructures to be robust enough to resist GLOF destruction, and
6) relocating the inhabitants to the places of safety.

Needless to say that item 1 is the most essential and important prerequisite for planning mitigation of a GLOF hazard downstream. The GLOF damage at a given point can be evaluated if we can estimate the water level, velocity, density and discharge through the section. If we get the information of glacier lake outburst event immediately (item 2), engineers involved with the infrastructure (say, a hydropower station) and inhabitants downstream may have enough time to be able to make appropriate preparations against the on-coming GLOF and to escape with their movable properties. In this connection the installation of a proper monitoring system at / near the lake and the establishment of a network of warning system are the most desirable prerequisites as GLOF mitigation countermeasures. The items 3 and 4 may not be cost-effective options. Benefit / cost and risk analysis, however, could be done to examine the effectiveness. The item 5 should be considered in the planning phase of infrastructure development. This option may also be applicable in the case of existing infrastructures. Relocation of people (item 6) may sound an easy option but, in reality, it is beset with practical problems as it involves the loss of inter-relationships and social network among the inhabitants, and other socio-cultural issues. The cultivated lands which are the living base for people's subsistence can not be removed. It may be an effective measure to restrict construction of new houses in places likely to be affected by GLOF.

The measures stated above allow of the occurrence of GLOF and only aim at mitigating its damage to inhabitants and infrastructure. It should be noted that the GLOF event results in damage of not only to inhabitants and infrastructure but also to the ecological system and environment along the river. GLOF impact leads to extensive aggradation and heavy erosion of the riverbed, bank undercutting and many landslides from both slopes along the river channel. It is strongly recommended that prevention activities as mentioned in Section 8. 1 should be undertaken to abort potential damage by GLOFs.