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GLOF mitigation strategies - lessons learned from studying the Thulagi Glacier Lake, Nepal

J. Hanisch[1], A. P. Pokhrel[2], W. E. Grabs[3], A. M. Dixit[4], and J. M. Reynolds[5]

[1]*Federal Institute for Geosciences and Natural Resources, Hannover, Germany*
[2]*Department of Hydrology and Meteorology, Kathmandu, Nepal*
[3]*Federal Institute for Hydrology, Koblenz, Germany*
[4]*SILT Consultants P. Ltd., Kathmandu, Nepal*
[5]*RGSL, Mold, Wales, UK*

ABSTRACT

The results of an interdisciplinary study of the Thulagi Glacier Lake in Manaslu Himal in 1996 were in part surprising: different from remote sensing and geomorphologic interpretations, the Thulagi Lake is not dammed by a terminal moraine. Instead, the natural dam is composed of a huge, apparently old, thick, and slowly melting dead-ice body covered by mainly lacustrine sediments. Therefore, the most common mechanism of GLOF generation, the breaching of the damming terminal moraine by overtopping surge waves, can be ruled out in this case. Another important result of the field studies at the Thulagi Lake was the finding that most of the sediments of the dam area are lacustrine silts and fine sands with erratic boulders in-between. That implies that these sediments (hitherto believed to be of glacier origin) were deposited in a former lake.

This case study demonstrates two fundamental facts: (i) each individual glacier lake has got its own development mechanism without the knowledge of which reliable statements on the lake's stability and its potential outburst hazard cannot be made, (ii) the hazard assessments of a glacier lake can only be done successfully in a multidisciplinary approach and by extensive field work. Remote sensing techniques still do have their limitations in this domain.

Mitigation strategies have to focus on both: the GLOF hazard as well as the vulnerability of the area in the downstream. Only a combination of these two factors (by using the formula: disaster risk = hazard x vulnerability) can lead to results that can convince the decision-makers on the need and effectiveness of mitigation work.

INTRODUCTION

Glacier lake outburst floods (GLOFs) are among the most frightening natural hazards in all glaciated mountain areas of the world. The glacier lakes, at times huge in size, are formed due to damming either by moraines or by glacier ice. The Himalayas witnessed in the past few decades the development of numerous glacier lakes caused by the fast ablation of glaciers (Ives 1986; Vuichard and Zimmermann 1987; Grabs and Hanisch 1973; Mool 1995; Reynolds 1995). Huge lakes have developed behind morainic dams or by the advance of neighbouring glaciers. Many millions of cubic metres of water are stored in such natural reservoirs. The failure of the dams can result in the instantaneous water discharge of up to several thousand cubic metres per second and the lakes are emptied within a few hours only. By picking up the abundantly available debris of glacial and fluvial origin along the flow path, the floods in most cases are instantaneously converted into huge debris flows. These can attain high velocities in the narrow and steep valleys of high mountain ranges and may reach areas more than 100 km downstream (e.g. Eisbacher and Clague 1984). Finally, they use to turn into fluvial floods again, which may be recorded much farther downstream.

THE THULAGI GLACIER STUDY

The Thulagi Glacier Lake in the vicinity of Manaslu Himal in western Nepal (Fig. 1) is situated at an altitude of about 4,100 m (Plate 1). It stores a water volume of about 30 million m^3 (WECS 1995). A potential GLOF from an outburst of this lake could not only devastate the villages and infrastructure along the Marsyangdi Valley but could also endanger an existing hydropower station and two others that are now in the planning stage (Fig. 1).

In 1996, the Department of Hydrology and Meteorology (DHM), Kathmandu, was assigned to carry out an assessment of the potential GLOF hazard of the Thulagi Glacier Lake. The study was implemented in close cooperation with the Federal Institute for Geosciences and Natural Resources (BGR), Hannover, with the financial sponsorship of KfW, the German Development Bank.

The results of the interdisciplinary study undertaken by a team of engineering geologists, hydrologists, glaciologists, geophysicists, and surveyors in the autumn of 1996 were in part surprising (Pokhrel et al. 1997): different from other glacier lakes and differing from remote sensing and geomorphologic interpretations (WECS 1995; Völk 1998), the Thulagi Lake is

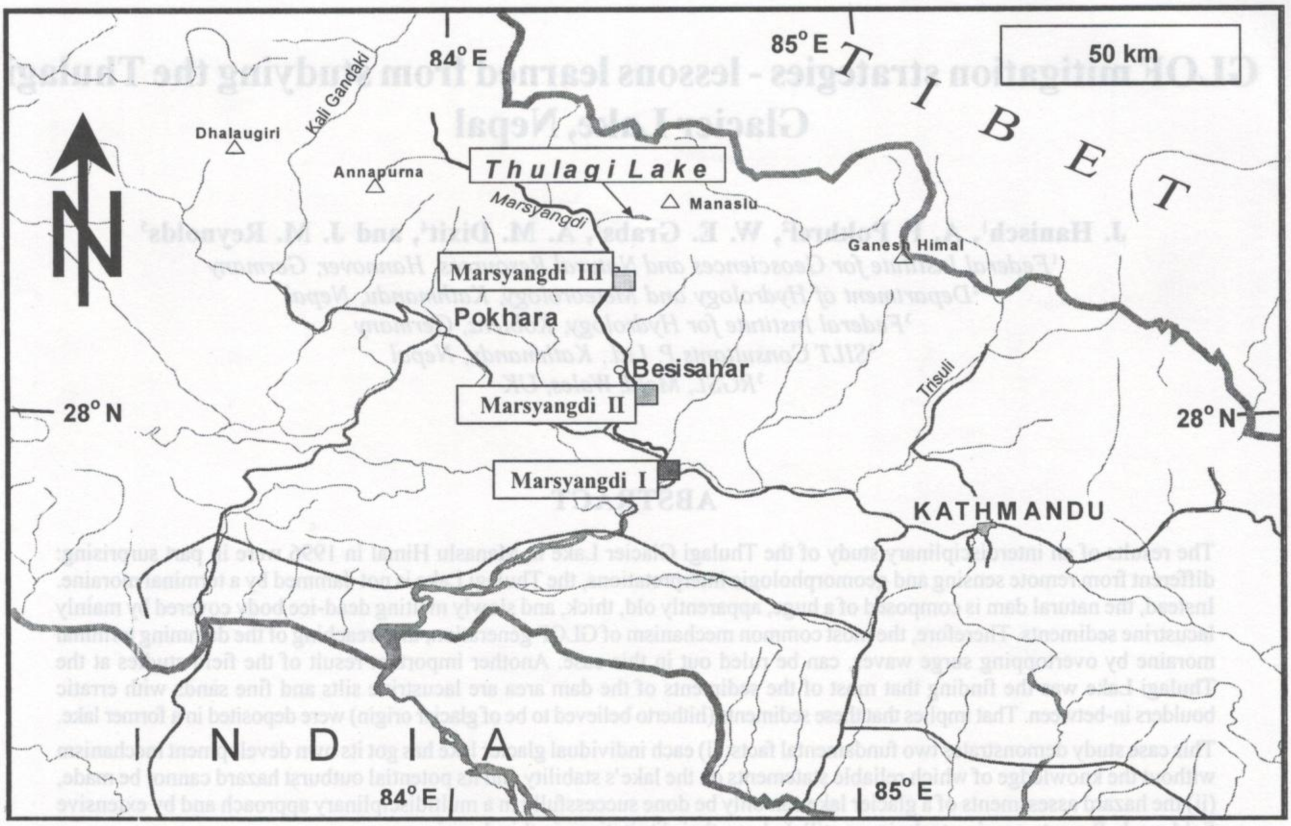

Fig. 1: Map of Central and Western Nepal showing the Thulagi Glacier Lake near Mt. Manaslu (8,156 m), and existing (Marsyangdi I) and two other hydropower projects

not dammed by a terminal moraine. Instead, the natural dam is composed of a huge, apparently old, thick, and slowly melting dead-ice body covered by mainly lacustrine sediments (cf. geo-radar image in Fig. 2). Therefore, the most common mechanism of GLOF generation, the breaching of the damming terminal moraine by surge waves, was ruled out in this case.

The melting rate of the buried ice body was calculated to be very low, because it is covered by up to 35 m of debris. It is expected that the hidden ice body will continue to melt slowly allowing, with time, the slow and un-dramatic lowering of the lake level. Based on these facts, the risk of development of a GLOF disaster for the Thulagi Lake was excluded under the present conditions.

Another important result of the field studies around the Thulagi Lake was the finding that most of the sediments of the dam area are horizontally bedded lacustrine silts and fine sands with erratic boulders in-between. This implies that these sediments (hitherto believed to be of morainic origin) were deposited in a former lake. This should have occurred in another glacier lake most likely dammed by an advancing glacier from a tributary valley (Hanisch et al. 1998). Most of the ridges that appear to be moraines at the first glance were in reality carved into the lake sediments and thus are the remnants of erosional processes.

This case study demonstrates a series of important lessons:

(i) apparently, every individual glacier lake has got its own development history and mechanism;

(ii) the knowledge of the development of the lake is necessary for responsible statements regarding its stability and potential outburst hazard;

(iii) the outburst hazard assessments of a glacier lake can only be done successfully using a multi-disciplinary approach and by undertaking extensive field work; and

(iv) remote sensing techniques still have their limitations in this domain (cf. Huggel 1998).

GLOF RISK MITIGATION STRATEGIES

The assessment of a GLOF risk can be carried out either by examining one or several specific glacier lakes in one single watershed or can include all known glacier lakes of a certain high mountain region, resulting in the risk and hazard evaluation for the whole region.

The GLOF hazards can be managed either by implementing preventive measures such as the lowering of the level of the glacier lake, or by such provisional measures as installing early warning systems or relocating the vulnerable infrastructure to higher levels of the threatened valleys.

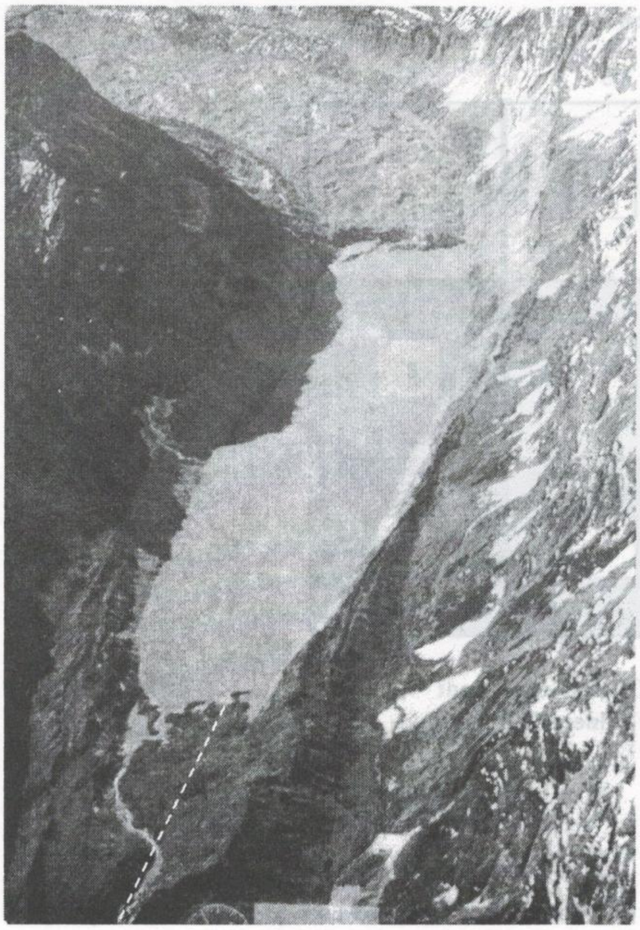

Plate 1: Oblique aerial photograph of the Thulagi Glacier Lake (WECS 1991) with the complex pattern of ridges in the foreground. Location of geo-radar line of Fig. 2 is also indicated.

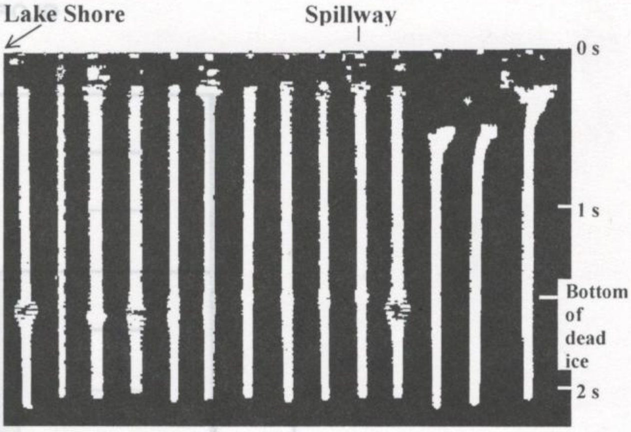

Fig. 2: Typical geo-radar profile compiled from individual survey points (for location see Plate 1)

GLOF risk assessment

In disaster management, the risk of a catastrophe has been defined as the product of hazard (probability of occurrence) and vulnerability (Varnes 1984):

Risk = Hazard x Vulnerability.

That means, the risk of GLOF disaster can only be defined if there is a human community or infrastructure vulnerable to the damage in the valley downstream of a glacier lake (from the point of view of mankind). The GLOF risk assessment therefore principally consists of two phases: the hazard evaluation of a potential outburst and the appraisal of the vulnerability of the downstream valley.

GLOF hazard evaluation

Based on the experience of existing studies, the determination of GLOF potential has to concentrate on the following criteria:

- examination of the size and growth of the lakes (dependant on the retreat or melting rate of the glaciers);
- assessment of the steepness and stability of the glacier fronts;
- assessment of the hazard of ice fall, avalanches, or rockfall into the lake;
- examination of the type of material damming the lake and its stability; and
- assessment of the hydrological regime of the lake.

With these data and information, a ranking of the GLOF risk can be established for an individual lake or for a number of lakes in a certain region. The quality of this ranking will apparently depend on the quality of the collected data and their evaluation. As discussed earlier, these criteria cannot be gathered and judged from desk studies using experience from other areas and remote sensing techniques alone. The decision as to which of the apparently dangerous lakes should be examined in the field (requiring greater efforts in a harsh environment) can only be made after the second step: the assessment of the vulnerability of valleys downstream.

Vulnerability of the downstream valleys

Even a giant GLOF would not do too much harm to a valley that is totally uninhabited. Disasters are possible only in the presence of human elements. For the risk evaluation, it is therefore indispensable to check what type of damage could be done by such a devastating event. First of all, an inventory of all villages and their demographic characteristics, and of all types of infrastructure situated in the reach of a potential GLOF have to be registered. The same is true for existing and projected objects of regional or national interest, such as, roads, bridges, weirs, and any kind of installations for irrigation or power generation. In

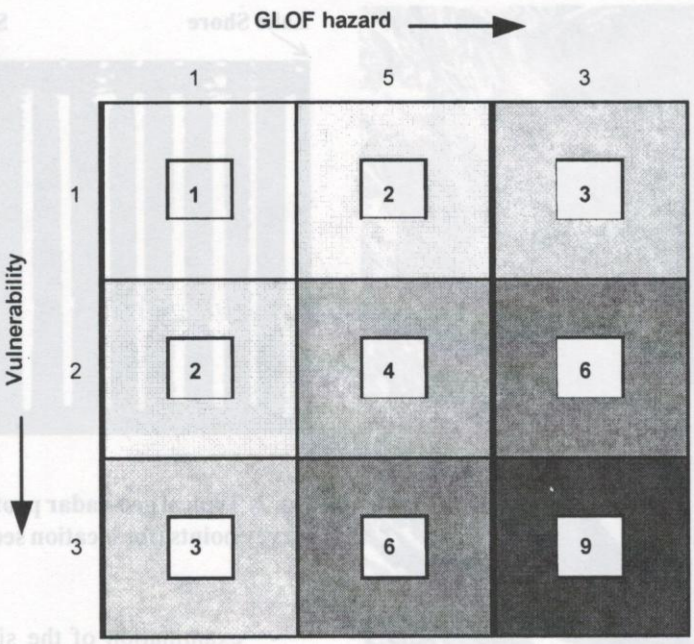

Fig. 3: Matrix of GLOF risk assessment (Risk = Hazard x Vulnerability)

the second step, the reach of a potential debris flow from a glacier lake outburst has to be estimated.

Prediction of GLOF reach by modelling

Definition of potential reaches of a GLOF – horizontally (down the valleys) as well as vertically (up the valley flanks) – is one of the most important and, at the same time, most difficult tasks in the field. The flow behaviour of a GLOF depends on a great variety of factors, such as, the peak discharge of the glacier lake, the amount of lose debris available for pickup along the upper part of the valley, and the steepness, straightness, and narrowness of the valley (Eisbacher and Clague 1984). Recently, some promising new attempts have been undertaken to bring light into the mechanical flow behaviour of debris flows, which is still rather enigmatic (Ter-Stepanian 1996). The initiation of debris flows is explained, either by the transformation from landslides (Iverson et al. 1997) or by channel-bed failure resulting from excessive flow of surface water (Tognacca and Bezzola 1997).

The most commonly used computer model for debris flow simulation still is the DAMBRK model (Fread 1988; Meon and Schwarz 1993; Costa 1997). It is a relatively simple, one-dimensional, surface-water model. It is able to give a first idea of the hydrographic levels reached by the flow during the passage of the current at a given cross-section. Apart from being one-dimensional, its main disadvantage is that it is based on the medium water (of density one) and not on debris/water mixtures of up to 2.4 t/m^3 (as observed in full-scale experiments by Khegai et al. 1992).

The so far best-established physical model seems to be the one by Iverson (1997). It tries to avoid some of these weaknesses by taking into consideration the vibrational kinetic energy of the boulders and the pore pressure of the fluid in-between. It is, however, yet far from being a user-friendly tool for the engineering practice.

In Fig. 3 an attempt is made to demonstrate graphically the relationship between GLOF risk and the vulnerability of the downstream valley according to the given formula. It turns out that only the fields with factors 9 and 6 are of practical interest for any potential remedial measures. A first priority for prevention works should be clearly given to field 9 where an eminent GLOF risk is combined with the high vulnerability of the valley below. In the two cases of "6", the decision-makers have to examine carefully which priority they would give to either prevention works at the lake or mitigation measures along the threatened valley.

GLOF PREVENTION METHODS

A great variety of GLOF prevention methods have been proposed since the first practical prevention measures were implemented in the Andean mountains of Peru (cf. Lliboutry et al. 1977; Reynolds 1992). They normally concentrate on the lowering of the level of the glacier lake to prevent the failure of the natural dam or (in case the dam breach can not be prevented) on minimisation of the potential damages down-valley. Grabs and Hanisch (1993), Mool (1995), and Reynolds (1995) have summarised the known methods. Among them, the use of hydraulic siphons is tempting, since it is not dependent on any power supply, which is difficult to arrange in remote areas. It has been successfully tested in Peru (Reynolds 1992), Kazakhstan (Popov, personal communication 1999), and Nepal (WAVIN 1995).

This system takes advantage of the difference of the hydraulic potential between the inlet and outlet of a water-filled pipe. The limitation of the possible suction head is governed mainly by the atmospheric pressure but other factors also influence the performance of such a device (cf. Grabs and Hanisch 1993). Its major advantage is that the terminal moraine damming the lake is left untouched. Experience has taught, however, that in the harsh conditions with extreme differences in temperature, a series of technical problems had to be resolved, especially with the design of the joints. On the other hand, if major quantities of water have to be discharged, the method suffers from its technical and financial constraints.

CONCLUSIONS

The risk assessment of a potential glacier lake outburst consists of two principle phases: the hazard evaluation of an outburst and the evaluation of the vulnerability of the downstream valley. For both factors, a ranking system has to be established. The GLOF vulnerability of a valley depends, first of all, on the reach of the debris flow generated by a glacier lake outburst and on the existence of communities and infrastructure within that reach. The latter is rather easily assessed. The calculation of the potential reach of debris flows depends, however, on a great variety of factors and has not yet been resolved satisfactorily.

The same is true of the hazard assessment of a glacier lake. Experience has demonstrated that remote sensing and geomorphological techniques have their limitations, and that without a detailed field examination (partly under harsh working conditions) a final judgement on the bursting hazard cannot be made. Furthermore, these investigations have to be carried out employing a multidisciplinary approach, since, e.g., none of the glaciologists, geomorphologists, hydrologists, geophysicists, and engineering geologists are able to cover the acquisition and analysis of a wide spectrum of data governing the history, present stability status, and future development of a glacier lake.

Mitigation strategies have to weigh carefully the two factors using a matrix to arrive at a final risk ranking of a series of lakes. After this, the necessary disaster prevention measures have to be implemented. These could consist either of GLOF prevention measures at the lakes themselves or of mitigation measures in the valleys downstream of the lake. GLOF prevention measures need a thorough examination of all the factors controlling the system: glacier–lake–dam, and the surrounding slopes to exclude the possibility of a man-triggered disaster (like the one reported by Lliboutry et al. 1977 from Peru). Mitigation measures in the threatened valleys involve mainly relocating the villages, roads, and bridges to levels out of the foreseeable reach of the debris flows that are likely to be generated by GLOF. For the calculation of these vertical as well as horizontal reaches, the existing debris flow computer models have to be improved considerably.

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