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Title: GLOF Risk Assessment in Hindu Kush-Himalayas (HKH) Region in the Era of Climate Change

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Abstract

Glacier lake outburst floods (GLOFs) have claimed numerous lives and have inflicted high costs in destroyed infrastructure and property in Hindu Kush-Himalaya region (HKH) region. Few commendable studies indicate glacier retreat, a possible cause of GLOF; but these work are confined to certain regions and are based on short observations, limited temporal data on hydro-meteorology and the indirect evidences. The process of climate warming further complicated the impact by developing potentially dangerous glacial lakes within the HKH region. It is clear from case studies that proactive decision making to prevent possible disaster is imperative. Glacial lake outburst flood risk is a reality in the Hindu Kush-Himalaya region and can be reduced by implementing various structural and non-structural measures. Studies on GLOFs in HKH region have so far concentrated on an inventory of glacier lakes, documentation of previous GLOFs and largely qualitative descriptions of glacier lake properties. The strategy towards GLOFs discussed in this paper is to provide a detail background of the formation of dangerous Glacier Lake Outburst Floods in the HKH region as a result of global climate change, with direct impacts on terrestrial change and human vulnerability and adaptation. An understanding of the hazard advances, effective warnings should reach every person at risk in a timely manner. There is a need to accelerate inter-governmental collaborative integrated research on glacial hazards and GLOF risk management. Hence proactive responses to threats from glacial lake outburst floods are essential for countries in HKH region where the risks are high and likely to increase due to glacial retreat as the climate changes.

Introduction

Global climate change and the shrinkage or retreats of glaciers throughout the world are hot topic of discussion and debate among scientific community in 21st century. High altitude ice cores reflect significant increases in temperature over the last few decades, resulting in glaciers and ice caps disappearing altogether in some places **(Schubert, 1992).** The global change in temperature results in the potential danger of increasing the frequency mountainous hazards and accelerating human activities. Mountain hazards are commonly landslide,

avalanche, floods, flash floods, glacier lake outburst floods which rather as natural event resulted in devastating effects with human interferences. Glacier Lake Outburst Floods (GLOFs) are the most unpredicted catastrophic occurrence, their path of destruction which can exceed 100 km downstream the outburst location **(Post & Mayo, 1971)** and their potential for destruction of settlements and infrastructure have been the subject of numerous scientific literatures. The Hindu Kush-Himalayan region forming the largest body of ice outside the polar latitudes is no exception. With the onset of climate warming about 1850-1905 (generally considered as the end of the Little Ice Age), many glaciers throughout the world, including in the HKH region, began to thin and their termini to retreat. The extensive permanent ice and snow cover extending for about 3,500 km from the Hindu Kush of Afghanistan and Pakistan in the northwest, through the Himalayas of India, Nepal, and Bhutan in the central part, to the Hengduan Mountains in southwest China in the east and also forms the headwater supply of some of the world's largest rivers. This in turn is vital for the provision of life supporting water and hydroelectricity for almost one-third of the world's population, living in the lower river basins beyond the mountains.

The amalgamation of extremely high mountains, high seismic activity, and steep slopes is also responsible for a wide range of natural hazards, including landslides, flash floods, avalanches, and glacial lake outburst floods. This is accompanied by formation of melt-water lakes, both on the glacier surface and in front of them. Already several, like Imja Lake and Tsho Rolpa, are more than two kilometres long and about 100 metres deep. These lakes are usually dammed by end moraines; these are mounds of rubble carried down the valley by glaciers and deposited as ridges when the glaciers were much larger than today. Because the moraines are not well consolidated and frequently contain an ice core that is also melting they are often unstable. This means that glacial lakes are in danger of bursting their moraine dams to cause a catastrophic flood (GLOF) in the valley below. Several outbursts have already occurred with attendant loss of life and property, although it should be noted that the actual threat is often exaggerated. The IPCC Second Assessment Report **(IPCC, 1996)** has recommended that 'future research needed to understand and predict effects of climatic change on mountain regions should represent balance and coordination between field studies (including paleo-environmental data collection), monitoring, experimental studies, and modelling. Following identification of lakes that pose a threat, measures can be taken to reduce the danger and install early warning systems. Monitoring ice and water resources, promoting community resilience and preparedness for disaster risk reduction, and ensuring the sharing of upstream-downstream benefits are priority areas in ICIMOD's programme. The objective of this paper is to provide a detail background of the formation of dangerous Glacier Lake Outburst Floods in the HKH region as a result of global climate change, with direct impacts on terrestrial change and human vulnerability and adaptation. This work can be tool for planner and policy maker to facilitate regional collaboration aimed at reducing the glacial lake hazard.

Stability of Glacial Lakes in HKH region

GLOF is a catastrophic discharge of water from the glacial lakes due to failure or breach of ice or moraine dam, formed at the end of these lakes. Moraine-walled lakes are structurally weak and unstable, so there is significant danger of catastrophic flooding due to slope failure and slumping **(Dahal, 2008; Ives, 1986; Rana et al., 2000)**. It is because of the fact that the Himalayan glaciers produce very rich debris that make relatively large lateral and end moraine, compared to others glaciers in the world. Ice dammed lakes are very rare, and considered less dangerous for flood hazard **(Yamada et al., 1993)**. Glacier lakes, which

occupy old glacier tongue basins of retreating glaciers, through valley glaciers and cirque glaciers with old, stabilized end-moraines formed during the Pleistocene period, are relatively stable and outbursts less likely. On the other hand, glacier lakes which are in contact with an active glacier and which are dammed by unconsolidated moraines resulting from periods of recent glacier advances in the last 300 years, especially the last "Little Ice-Age" are potentially unstable and more prone for outbursts. These recent moraines have usually steep slope angles and, especially the lateral moraines, slope angles that may exceed the theoretical internal friction value of the moraine materials. The recent terminal moraines have mostly narrow crests and may contain ice lenses or cores. At least twenty GLOF events recorded in Himalaya in the last seven decades that resulted in heavy loss of human lives and their property, destruction of infrastructure besides damages to agriculture land and forests. The potential for loss of life and damage to infrastructure due to glacial lake outburst floods is varied depending on factors such as the size and depth of the lake, the nature of the outburst, the geomorphology of the river valley and elements exposed to the flash flood **(Dixit & Gyawali, 1997; Shrestha et al., 2010).** The assessment of the stability of glacier lakes is an important criterion for the selection of glacier lakes where flood mitigation and/or outburst prevention techniques are to be executed with priority.

The International Centre for Integrated Mountain Development (ICIMOD) and its partner institutes, in collaboration with United Nations Environment Programme /Regional Resource Centre for Asia and the Pacific (UNEP/RRC-AP) carried out a systematic inventory of glaciers and glacial lakes of Nepal and Bhutan in 1999–2001. Later, the study was continued in collaboration with the Asia-Pacific Network for Global Change Research (APN) and the global change SysTem for Analysis, Research and Training (START), and expanded to all the ten sub-basins of the Indus River in Pakistan, all sub-basins of the Ganges in the Tibet Autonomous Region of the Peoples' Republic of China, and Tista River Basin along Himachal Pradesh Himalaya and Uttaranchal Himalaya of India (http://www.icimod-gis.net/glof/glof.php). Once the study on Arunanchal Pradesh Himalaya and Jammu & Kashmir Himalayas, northern Afghanistan and Myanmar area are completed, the entire database of the Hindu Kush–Himalayan region will be served at the scale of 1:50,000.

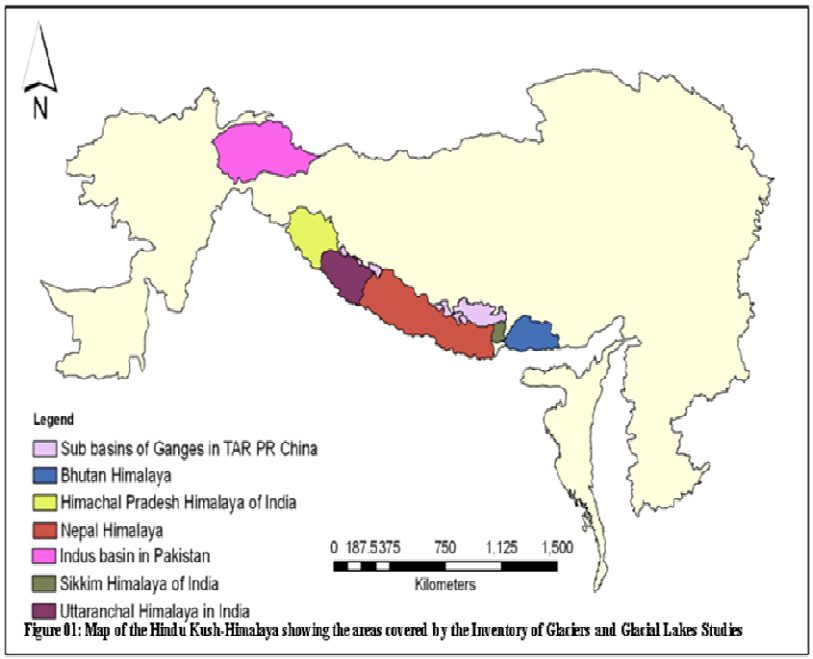

Figure 01: Map of the Hindu Kush-Himalaya showing the areas covered by the Inventory of Glaciers and Glacial Lakes Studies

Risk Assessments of GLOF due to Climate Change

The recent global warming phenomenon have ushered scientist to consider the expansion of glacier lakes and their outburst. While some large and high altitude glaciers in the Karakoram are reported to have

advanced **(Hewitt, 2007),** the majority of glaciers in the eastern Himalaya have retreated in the past decades **(ICIMOD, 2009)**. It is widely believed that changing temperatures may be the cause of the retreat (**Bajracharya et al., 2008; ICIMOD, 2009).** The most significant GLOF event since detailed recording started occurred in Dig Tsho lake at Bhote Kosi in Nepal in 1985. It destroyed a nearly completed small hydropower project (estimated cost of US$ 1.5 million), numerous foot-bridges, trekking trails and caused loss of many lives **(Mool et al., 1993)**. A huge rapid landslide dammed the Yigong river (China) on 9 April 2000. After two months, on 10 June 2000, the outburst flood from the landslide dam extended 500 km downstream uptil the state of Arunachal Pradesh, North-Eastern India causing heavy damages **(Zhu and Li, 2001)**. In June 2005, outburst of landslide dam lake on Parechu river (China) caused a transboundary flood in Himachal Pradesh (India).

GLOFs are common geomorphic unit in HKH region but also time dependent variables as melting processes, Lake water level fluctuations, seepage, glacier movements etc. are varying with seasonal climatological and hydrological conditions. The geomorphological setting of glacier lakes and their hydrological behaviour are important general indicators for glacier lake stability. The glacier retreat implies a serious concern for water availability for household, agriculture, power and industry for 400 millions living in downstream Indo-Gangetic and Brahamaputra plain. The water demand for agriculture, industry and urban sector in Nepal, India and Bangladesh is progressively growing. The decline in snow cover would mean a condition of water deficit which is a serious threat to food security, energy availability and industry. In the High and Trans-Himalaya region the decline in snow cover would cause serious impact to mountain ecosystem and the livelihood base of the local people which is based on snow melt water fed agriculture and pasture for livestock grazing. The risk associated with glacial lake selected for the application of outburst prevention techniques, the lake must be continuously monitored as well as glacier observations made and the geotechnical stability of the dam monitored. The different mitigation techniques available are artificial lowering of the water level (draining) and installation of early warning systems. Furthermore, given adequate mitigation measures, the glacial lakes can be regarded as a form of water storage and valuable potential source of water and hydroelectric power. The need of time is for integrated research collaborative for risk assessment by using engineering geologists, civil engineers and experts in snow and glacier hydrology.

Future Research Perspectives

The studies carried out in HKG region are confined to certain region and also are based on short observations, limited temporal data on hydrometeorology and the indirect evidences. However, these studies have made the government and the community at large aware of the risk of GLOFs, implicated glacier retreat, climate change, and urged to look for better adaptation measures. The current knowledge and ongoing research are still early to come up with firm conclusions about the state-of-affairs. It is now possible to assess the outburst flood risk of a lake and possible damage to infrastructure and livelihoods to some extent, using remote sensing and mapping. Geospatial technology can be the essential tool for identification of those lakes that require detailed investigation in HKH region due enormous extent and poor accessibility. For risk assessments require a repeated monitoring system using time series satellite images is necessary to identify changes over time. This technique

has to be integrated with glaciological and geotechnical field investigations of priority lakes for determining the real degree of glacial lake outburst. It facilitates rapid and complete coverage of large and extremely remote mountainous areas, thus allowing potentially dangerous localities to be pin-pointed for closer inspection. This is important because the total area of such localities will be a small percentage of the entire region under initial survey. The other methods for assessing and mapping the vulnerability of downstream communities combining with modelling of the downstream flood path are to discover the likely risk. It is vital to identify potentially dangerous glacial lakes and the risks they pose, and highlight the critical ones. Planners, policy makers, development workers, and scientists need to develop and implement appropriate mitigation measures including the implementation of early warning systems. The effective implementations of these policies are possible only when local stake holders are involves in the process of mitigation and prevention.

The future investigation should try to develop standardised glacial lake inventory of the entire HKH region keeping in view the potential for serious losses to glacial lake outburst appears to be growing steadily. The inventory has to be updated periodically by using progressively inexpensive high resolution satellite imagery and more sophisticated methods for its analysis. The availability of current information and communication technology (ICT) suitable for rural application of early warning systems should be evaluated. This will enhance possibilities for installation of the most up-to-date systems to ensure near-instant warning of danger to a large population. There are examples of comparatively simple and highly effective CDMA (Code Division Multiple Access) and SMS (Short Message Service) communication systems in place for early warning against tsunami; the applicability of these should be assessed. The different government in HKH region has to develop national guidelines to deal with the problem of potential glacial lake outbursts and GLOF risk management. There is a need to accelerate inter-governmental collaborative researches on glacial hazards and GLOF risk management as well as development of a mechanism of inter-governmental collaboration for sharing data and information. A regional convention of inter-governmental expert groups should identify and make recommendations on details of collaboration and the role of national governments, and draw action plans for GLOF risk management.

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