Reducing Climate Change Induced Risks and Vulnerabilities from Glacial Lake Outburst Floods in Bhutan

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Introduction

There is a growing scientific consensus that anthropogenic induced climate change has been occurring since the beginning of the industrial revolution. Impacts of climate change are felt all around the world, particularly in climate sensitive regions with vulnerable ecosystems. For instance, shortage of water resources due to the retreating and shrinking of glaciers and hazards related to Glacial Lake Outburst Floods (GLOFs) are serious climate change impacts felt among the communities residing in mountain environments. Given the sensitivity of mountain environments, especially the cryosphere, ever-rising air temperature has serious consequences for natural and socio-economic systems in the area.

A major proportion of Bhutan's population is settled in fertile valleys along a number of river systems. When GLOF occurs along rivers which are sourced from glaciers and glacial lakes the lives and property of many people are at risk. Such devastating effects can still be seen today from the last GLOF that took place in Bhutan in 1994 along the Puna Tsang Chu valley. Not only are lives and property endangered but also important infrastructure such as hydroelectric dams that are situated along these rivers. If Gross National Happiness[1] is the pride of the Bhutanese people then the driving force behind it is the hydroelectric power stations, which are driving the Bhutanese economy forwards with a contribution of about 45% to national revenue and 12% to GDP growth.

The Government of Bhutan has taken a step towards adapting to climate change by developing a National Adaptation Program of Action (NAPA), coordinated by the National Environment Commission (NEC). The main objective of the NAPA has been to identify and address the most prominent issues related to climate change. Three projects from the Bhutan Department of Geology and Mines have been prioritized during the NAPA formulation. These are: artificial lowering of lake water level in the Thorthormi lakes; installation of early warning systems in Punakha-Wangdi valley; and hazard zonation mapping in Chamkhar.

The Netherlands Climate Assistance Program (NCAP) supported a GLOF hazard zonation mapping exercise along the Puna Tsang Chu from Khuruthang to Lhamoizingkha. This project was not listed under the NAPA projects but was nevertheless considered important because: i) a hazard zonation map already exists from Lunana (source) to Khuruthang in Punakha, which was completed as part of an earlier Austria-Bhutan project; ii) a number of planned large hydroelectric power schemes are situated on the Puna Tsang Chu; and iii) earlier studies with Austrian and Japanese researchers demonstrated that lakes in Lunana still pose GLOF threats and recommended that hazard zonation mapping be carried out in this area.

1 http://www.grossnationalhappiness.com/

Objectives

During the joint project between the Department of Geology and Mines with the experts from the University of Vienna, Austria, a hazard zonation map was prepared from the source of the Pho Chu to Khuruthang in Punakha. But the remaining area between Khuruthang and Lhamoizingkha remained an area without a hazard zonation map for Glacial Lake Outburst Flood (GLOF). A need for similar maps for the remaining area was realized considering the following reasons:

- The presence of critically dangerous glacial lakes at the source of the Pho Chu;
- The large number of settlements along the fertile valley bottoms along the Puna Tsang Chu;
- Large hydropower plants which both exist and which are in the pipeline on the Puna Tsang Chu; and
- Other developmental infrastructure along this river valley.

Therefore the main aim and objective of the DGM-NCAP project is to prepare a "hazard zonation map" from Khuruthang in Punakha to Lhamoizingkha on the Bhutan-India border under Dagana Dzonkhag, thus covering the entire area along the Puna Tsang Chu with a hazard map for GLOFs in the future. These maps are expected to serve as a tool to guide the planners and decision makers:

- As a tool for any future developmental activities along this river; and
- As a guide for the local communities and local authorities to minimize the damage on the lives and properties of the people.

Material and Information Used

For the purpose of data analysis and hazard map production the following materials used are:

a. Topographical maps
Topographical maps for most of the areas where accessible and critical were prepared using surveying instruments ("Total Station"). The close contours generated were then used for the data analysis. For those parts where the accessibility was not possible, the contours generated from the SRTM were used. In fact the slope which forms one of the important aspects in the data analysis part was generated using these contours.

b. Satellite images
Given the importance of the project, a set of Quick Bird images were procured which have a resolution of 0.6m.

c. Land use maps
These maps were prepared in the field based on the field verification and using the satellite images as base material.

d. Material maps
These maps were also prepared in the field based on the field verification and using the satellite images as base material.

e. Slope maps
For the areas which were accessible and critical, surveys were conducted using "Total Station" and contours generated from this were then used to generate the slope maps. For those areas where it was inaccessible for the team to conduct surveys, SRTM was used to generate contours and based on these contours slope maps were prepared.
f. Socio-economic information

All this information was collected in the field through interaction with the local vulnerable communities. The information covers a wide range of aspects which are listed below. This information was mainly collected to assess the vulnerability of the local communities should a GLOF occur in the Puna Tsang Chu basin.

Methodology

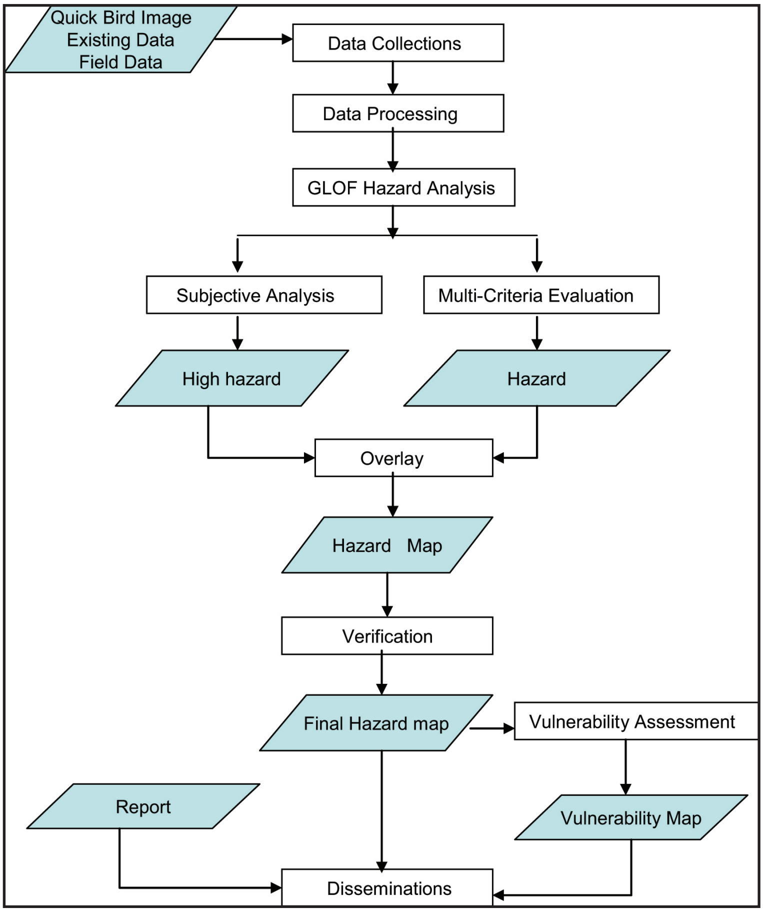

Figure 1: Overview of the Methodology

An overview of the methodology used in the preparation of hazard maps is shown in the above figure (figure 1). The whole process of the preparation of the hazard maps was kept very simple but all the technical aspects required were incorporated. Each of the steps followed in the above figure are explained in detail in the following section.

Data Collection

The data and information which were required for GLOF hazard zonation analysis and vulnerability assessment along the Puna Tsang Chu were collected through various means such as from existing data, field surveys and remote sensing data (Quick Bird images).

a. Remote sensing data

The Quick Bird images were procured to derive or extract the features and information which were necessary for GLOF hazard zonation and vulnerability assessment. There are three levels of quick bird image products: basic imagery, standard imagery and orthorectified imagery. For this project standard imagery was used. The standard imagery products were radiometrically corrected, sensor corrected, geometrically corrected and mapped to a cartographic projection and had a resolution of 60cm. Furthermore, the GPS observation in the project area was carried out for geo-rectification of the image to enhance the accuracy. The infrastructure and utilities which were extracted from the image included industry, public buildings, commercial buildings, residential buildings, government institutions, schools, roads, footpaths, bridges, historical monuments, power lines and telecommunication lines etc. The quick bird images were not only used for the above feature extraction, it was also used for the extraction of material type and land use.

There are various ways of extracting the feature from the image. In this project, visual interpretation and screen digitization was used applying geographic information system (GIS) and remote sensing (RS) technology. The GIS and RS offer appropriate technology for data capture, data integration, data management, storage, information extraction, routine manipulation, spatial analysis, decision making and visualization. They also offer strong tools to assess different hazards, risk, vulnerability, damage and much more. The extracted features were checked during the ground verification and updated.

b. Field survey data.

For assessing the impact of future GLOFs, the detailed socio-economic survey in the entire project area and the topographical (mainly contour line) survey using “Total Station” were carried out in the places where there are human settlements, development and the elevation is lower than the river. The data for the socio-economic survey consisting of infrastructure, population and livestock was collected from every household and recorded in the GIS format. The 1994 flood marks were also collected for validation and subjective analysis.

The socio-economic data collection was confined to settlements within a 250m buffer zone on either side of the Puna Tsang Chu. The existing data is the data and reports that are available through government agencies.

c. Existing (available) data

The existing data is the data and reports that are already collected and available with the various agencies:

1. Aster DEM (15m), Department of Energy
2. Administrative boundaries (Survey of Bhutan)
3. Topography Map 1:50,000 (Survey of Bhutan)
4. Reports on GLOF
5. Lake volume

d. Data processing

This is the preparation of spatial data for processing, the analysis required by the operating system graphically, or storage and processing of data by the computer using particular software. Data processing or information processing was performed on data in accordance with strictly defined procedures for a certain application, these included: i) conversion of data into a form that can be processed by the computer; ii) storing or processing of data by a computer; and (iii) data handling, merging, sorting, and computing.

The meta data was also collected for the existing data and analyzed. The information on the quality of spatial data allows users to determine a product’s ability to satisfy the requirements for his/her particular application.

e. Spatial data analysis (GLOF hazard analysis)

In this project, the GLOF hazard analysis was carried out with the combination of two methodologies namely a *subjective analysis and multi-criteria evaluation*. The detail of each of methodology is described below.

Multi-criteria evaluation is primarily concerned with how to combine the information from several criteria to form a single index of evaluation. In the case of Boolean criteria, the solution usually lies in the union (logical OR) or intersection (logical AND) of conditions. However, for continuous factors, a weighted linear combination is a usual technique. As the criteria are measured on different scales, they are standardized and transformed such that all factor maps are positively correlated with floods. Many decisions depend on identifying relevant factors (criteria) and adding their appropriately weighted value. Each expert in a decision or in the process of weighting criteria will have their own assessment of it based on their knowledge and experiences.

An ArcGIS Model Builder, commercial GIS software produced by ESRI has been used for this project of a GLOF analysis. A multi-criteria evaluation can be approached from two methods: a) binary method and b) weighted overlay method.

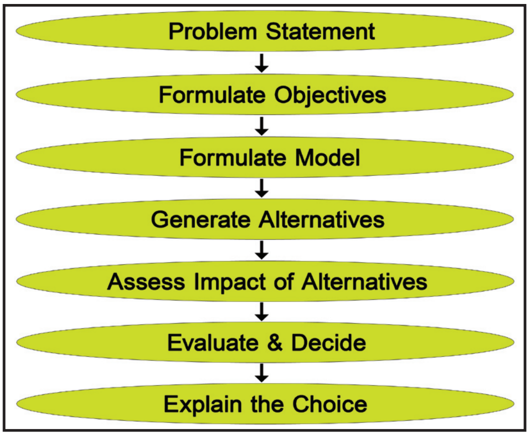

Figure 2: Multi-Criteria Evaluation Process

The purpose of the criterion weighting is to express the importance of each criterion relative to other criteria. The more important criteria had the greater weight in the overall evaluation. In this project two ranking methods were introduced and applied. Namely binary analysis and weighted overlay analysis. GIS should act as the interface between technology and the decision maker with integration MCE method onto the GIS. Different decision makers' maps apply different criterion and assign different weights for each criterion according to their preferences. The decision maker selects the criteria and compares them in a comparison matrix.

In multi-criteria evaluations, the preferences of the decision-maker are accounted for by the weighting placed on each of the criteria and sub-criteria. These weightings may range from equal importance of all criteria, to a ranking of most to least important or to a relative weighting of all criteria. The weights may be qualitatively expressed, quantitatively expressed or a mixture of both. In analyses which involve many different decision makers, this can be the most important and informative part of conducting the whole process. It allows stakeholders to express differing views explicitly and it helps identify those areas which are of most importance to them and which warrant careful investigation. When more than one decision-maker is involved (a so-called "5 group decision"), the process becomes more complex and controversial as now the preferences or weights are not unique but variable among the participants of the decision process. This process leads to a compromise decision making. A multi-criteria evaluation can be approached from two methods namely a) binary method and b) weighted overlay method. However, we have adapted the weighted overlay method for GLOF hazard analysis since it has some advantages over the binary method.

The binary method shows an impact function of the individual criterion with suitable layers for each of the separate criteria. The individual layers use "suitable" (1) and "non suitable" (0) or true and false. It is done by performing a simple map algebra using an AND operator. The result of this model ranges from 0 to 1 with many classes in between. In this model, the above mentioned criteria were implemented and came out with a most suitable, a suitable and a not suitable area for mining. The disadvantages of binary approach and results are shown as follow:

- The input layers have the same importance; and
- There is nothing in between suitable and not suitable.

The *weighted overlay method* is a technique for applying a common measurement scale of values to diverse and dissimilar inputs to create an integrated analysis (http://webhelp.esri.com dated 06-12-07). Weighting should be applied when not all aspects have an equal importance. It should be realized that the choice of a weight is most important, as it has a great effect through multiplication of the scores.

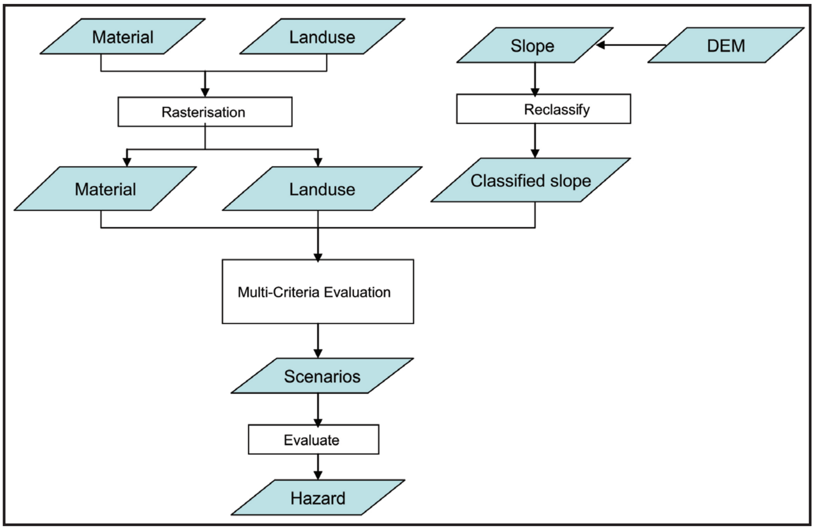

Figure 3: Work Frame of Weighted Overlay Process

Assigning the weights to factors is a critical element in suitability analysis. Weighting factors are often based on a mixture of implicit knowledge, personal experience and individual opinions. In order to reduce the subjective bias as much as possible, this research will use three weighting methods based on three different considerations in the study area.

Figure 3 shows the work frame of weighted overlay for GLOF hazard analysis to produce GLOF hazard maps.

In the process of multi-criteria decision making (MCDM), different stakeholders in the design process have different views about what is important, how that importance should be measured, and how various important factors can be combined. In multi-criteria evaluation, the important components are the weight and priorities assigned to each criterion which are weighted on quantitative measurement scales. The weights are applied or assigned to criteria when not all the aspects have equal importance in the evaluation. In the study the criteria have unequal importance so the weights have to be assigned to each criterion and this depends on evaluator opinion and decision makers.

The GLOF zonation mapping along the Puna Tsang Chu was carried out using a GIS based multi-criteria evaluation method taking the following causative factors:

- Land use/land cover;
- Type of soil/material along the river;
- Slope;
- Horizontal distance from river; and
- Height of river terraces.

The factors such as height of river terraces and horizontal distance from river were not used in the actual process of multi-criteria evaluation but were used in the editing process.

Considering an evaluation scale range of 1 to 3 (1- low hazard, 2- medium hazard, 3- high hazard), these causative factors were then assigned with different weights based on the importance of each factor in the events of GLOF. The weighted overlay process combines different types of data by assigning evaluation scale values and the amount of influence to the values in each thematic map.

Field Verification

Once our results are obtained from any spatial analysis, it is essential that they are verified. After the completion of hazard analysis, a team comprising a Glaciologist, Geologist, Geo-Informatics officer and survey assistant went into the field to carry out the field verification on the ground. The population and infrastructure data, land use/land cover, material type, terrace height and horizontal distance from the river centre were taken into account during ground verification. Not only were these taken into account, but also the historical data of GLOF events in the past particularly the 1994 GLOF and the information collected regarding the past GLOFs from the people. It was found that the results obtained were as good as could be expected.

Sensitivity Analysis

This is a discipline that plays a key role in the scientific modeling. It is the study of how the variations in the output of a model are apportioned qualitatively or quantitatively to different sources of variation of a model. The number of input factors involved in the analysis and objectives of the model play a major role in determining the final result. A sensitivity analysis on a model is to identify a parameter which has a substantial impact on a final result. A model which was created for suitability for a mining area in Bhutan was run to evaluate the impact of parameters. Sensitivity analysis depends on the error in the input data as criterion weights and criterion attributes. The impact of parameters on the final results was tested using sensitivity analysis and it was found that both land use and material had equal influence.

Setting

"The Land of the Thunder Dragon", "The Last Shangrila" and the "Land of the Peaceful Dragon" all refer to the tiny kingdom of Bhutan nestled in the eastern part of the Great Himalayan Range. Located between the two giants of China in the north and India on the remaining three sides, Bhutan is populated with just over 600,000 people. The terrain is mostly rugged and mountainous with altitude ranging from less than 100m in the south to more than 7,500m in the north within a north-south distance of less than 175km. 20% of the land area is above 4,200m and permanently covered with snow and ice, which form glaciers and glacial lakes.

The climate is dominated by the southwestern monsoon that originates from the Bay of Bengal. Normally the monsoon sets in the mainland by early June and last till early September. Just after the monsoon during the months of October and November, occasional rains occur which are basically the post-monsoon rains and can be quite severe. From November to March the period is usually dry but sometimes light showers may occur from the westerly winds, which brings rain to the foothills of the Himalayan range. The pre-monsoon season falls in the months of April and May which are accompanied by light showers, lightning and hailstorms. The record shows a rainfall of approximately 2,500 to 5,500mm in the southern foothills, 1,000 to 2,500mm in the inner valleys and 500 to1,000mm in the northern flank of the country. Climatically, the country can be divided into three zones: subtropical in the southern foothills; temperate in the middle or inner valleys; and alpine in the northern part.

All four seasons can be experienced in the country characterized by hot and humid in the southern foothills during summer and cool in winter, the middle valleys are warm in summer and cold in winter with pleasant spring and autumn with mild temperatures. Overall the variation in the climate is dominated by the altitudinal change.

Most of the rivers in Bhutan flow from north to south. The country is drained by five major river systems namely the Amo Chu, the Wang Chu, the Puna Tsang Chu or Sunkosh, the Manas, and the Nyere Ama Chu with many tributaries which are of appreciable size. Except for the Amo Chu and the Nyere Ama Chu the remaining three major rivers are formed by the joining of a number of tributaries. The Wang Chu is a collection of three main tributaries namely the Pa Chu, Ha Chu and Thim Chu. The Puna Tsang Chu or Sunkosh is formed by the amalgamation of another three main tributaries namely the Pho Chu, Mo Chu and Dang Chu. Similarly the Manas river system is a collection of another four major tributaries, the Mangde Chu, Chamkhar Chu, Kuri Chu and Dangme Chu. Almost all these rivers have their source in the perpetual snow and ice in the northern frontier of the country except for Kuri Chu which is a trans-boundary river having its source in China.

The impact of climate change is felt globally. It is projected that spatial average annual mean warming over the Asian region will be about 3°C by 2050 and about 5°C by 2080s as a result of the continued emissions of green house gases.

But what exactly is happening? Little research and studies have been done along the Himalayan Arc in terms of climate change, making it one of the least researched places in the world with scarce climate related data.

Some anecdotal evidence exists of impacts experienced by people living in the high altitude region of Manang and Mustang districts of Nepal. This includes recent erratic patterns and intensity of rainfall, which has impacted livelihoods to a great extent affecting houses built with traditional technology, fresh water resources and the agriculture sector, which basically depends on the availability of water at the right time. Declining Himalayan grassland due to low moisture content induced by less snow fall and snow cover in the mountain areas, has affected livestock adversely. Some locals feel that emerging mosquito related problems in places located above 2,700m may have been due to climate change. This anecdotal evidence seems to correlate well with the available scientific evidence and predicted scenarios.

As mentioned above climate data in the Himalayas is very scarce but studies on the analysis of available data in the Nepal Himalayas shows that the temperature is rising at an alarming rate. The warming seems to be consistent and has continued since the mid-1970s and average warming between 1977 and 1994 was found to be 0.06°C/year. It was also observed that the warming seems to be more pronounced in the higher altitudes in the mountains than low lying plains. A similar trend was also seen in the Tibetan Plateau.

Impact on the Himalayan Cryosphere

It is estimated that there are over 18,000 glaciers mainly concentrated in the following five major river basins: Lake Mapam Yumco; Ganga River basin; Yarlung Zangbo River basin (Barmhaputra); Indus River basin; and Sutlej River basin.

The huge field of ice and snow reserve supplies over 8.6 x $10^6 m^3$ of water annually, the region is called the “water tower of Asia”. The Himalayan Arc, considering its vast regional extent is home to millions of people with diverse cultures, lives and languages. The perpetual snow and ice fields in the Himalayas play a vital role in the socio-economy of the people living in the fertile valleys of this astounding mountain range, all establishing an ecological balance. The inhabitants of this region, who have traditionally lived in a delicate balance with their surrounding environment, are beginning to experience the impacts of climate change.

The glaciers in the Himalayan region are classified as the “summer accumulation” type, which implies that the glacier accumulates during the summer from the summer monsoon when ablation occurs simultaneously, making them very sensitive to changes in air temperature. A number of studies around the world show that the mountain glaciers are retreating. But across the Himalayas studies show that the glaciers are found to be shrinking more rapidly than the glaciers in other regions of the world and the retreating and shrinking has accelerated in the recent decades. The following section gives an overview on the retreating glaciers across the Himalayan Arc.

Shrinkage of 5.5% was observed in China’s glaciers over the last 24 years according to a study by the Chinese Academy of Science. *China Daily* (23rd September 2004) stated that as per the studies two thirds of the glaciers in China would disappear by the year 2050 and almost all by 2100 if the present trend of climate change continues. Within 12 years in Poiqu River basin there was shrinkage of 5.04% in the glacier area. The glacier valley in the Xixiabangma Mountains have retreated by 45m and 68m respectively since 1977.

Many studies were carried out on the fluctuation of glaciers in the Indian Himalayas Significant changes (retreat) were recorded in the last three decades.

When it comes to glaciological research activities in the Himalayas, the Nepal Himalayas are some of the most extensively investigated stretches across the Great Himalayan range. Most of the results show that the glaciers are retreating at a remarkable rate in the latter half of this century.

Glacier Lake Outburst Floods (GLOFs)

Fast decaying (retreating) glaciers leaving behind large debris of loose moraine with the formation of lakes behind it. These lakes grow in size with time and are dammed by unstable moraine ridges. These lakes could burst under various circumstances causing devastating floods in the downstream area, popularly known as Glacial Lake Outburst Floods (GLOFs). The impact of such floods on the lives and property of the people and infrastructures can be significant. In the Himalayan region it has been observed that the frequency of occurrence of GLOFs has been on the rise since the last half of the 20th century.

Cases of GLOFs were reported from almost all regions of the Himalayas, for example the 1985 Dig Tsho GLOF, the 1998 Tam Pokhari GLOF in Nepal; the 1964 and 1981 Zhangzangbo GLOFs in China and also the 1950s, 1960s and 1994 GLOFs in Bhutan. Besides these there were also cases reported from Pakistan. All these events caused huge damage to infrastructures of national importance and property and also resulted in loss of lives of both livestock and people.

National Economic Loss

The fast flowing rivers in countries like Nepal and Bhutan have a huge potential for hydropower generation. Being landlocked in terms of geographical locations, the national economy relies on hydropower generation (especially in the case of Bhutan where hydropower stands first in terms of national revenue generation). The long term impact of glacier retreat on river runoffs would be a disaster for such nations. Major industries which rely on river and stream water supply such as chemical, steel, paper and mining industries would be seriously affected. The water sensitive agriculture sector will be another major sector affected which may lead to serious consequences on crop production and consequently food security.

Climate Change and Natural Hazards in Bhutan

Bhutan, considering its geographical location and geological settings is prone to a number of natural hazards such as GLOFs, flash floods, landslides etc. The history shows at least three cases of GLOF in the past the most recent one being the 1994 GLOF from Luggye Tso. Flash floods have become a common phenomenon across the country. The most destructive one was the one that occurred in Pasakha, an industrial estate under Chukha *Dzongkhag* (district) in southern Bhutan in 2000. More recent flash floods include the one in Ranjung and the surrounding events in the eastern part of the country from which the country, is still in the process of recovering. Landslides blocking roads in the Himalayan region is not a new phenomenon but when whole villages are destroyed by progressing landslides or huge artificial lakes are being created by landslides, the risk posed can be a major national catastrophe. Such events has been witnessed in the eastern part of Bhutan like the Moshi landslide under Trashigang *Dzongkhag*, the Chaskhar landslide under Mongar *Dzongkhag* and the Tsati Chu artificial lake created by the landslide upstream in the Kuri Chu on which a 60 MW hydropower (KHPC) existed. The country has experience almost all types of mountain hazards in the past.

Now, with the impacts of climate change, the frequency of such natural hazards has increased tremendously and a new threat in the health sector has appeared in recent times. Already the climate related health problems such as outbreaks of dengue fever and malaria related problems are on the rise in southern Bhutan. *The Bhutan Times*, a weekly newspaper, reported a rising trend of dengue fever cases in southern parts of the country.

Another article from the same weekly paper reported unusually high temperatures in Phuentsoling and Gelephu town in southern Bhutan. During July and August 2006, summer temperature in Thimpu (approximate altitude 2,200m above sea level) reached 40°C and 33oC . Due to the intense heat there were some incidents where schools were closed down especially in southern Bhutan. The report also highlighted the decrease in rainfall throughout the country during this particularly hot summer.

Likewise there are more signs of climate change impacts seen in Bhutan recently. The impacts of climate change are usually associated with destruction but sometimes it can also be a positive shift for local communities. For example, Bumthang *Dzongkhag* in central Bhutan is located at an altitude of about 2,750m above sea level, and has never seen paddy cultivation in their district. But recently the Ministry of Agriculture (MOA) conducted a trial observation with positive results. Similar trends were also reported from the high altitude regions of Nepal.

Project Site

The project area lies in western Bhutan starting from Khuruthang in Puna *Dzongkhag* to Lhamoizingkha in southern Bhutan on the Bhutan-Indian border under Dagana *Dzongkhag*, covering a distance of approximately 180km with an altitudinal variation of 1,800m in Punakha to less than 100m in Lhamoizingkha. The area covered in our project includes part of Punakha, Wangduephodrang, Tsirang and Dagana *Dzongkhag*.

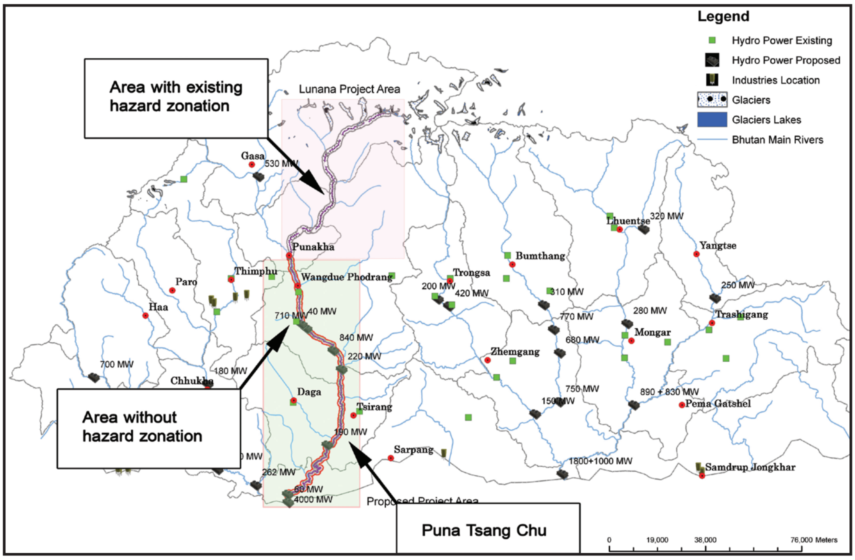

Figure 4: Map Showing the Project Area

Glaciers and Glacial Lakes in the Headwaters of the Project Site

Pho Chu and Mo Chu are the main tributaries, which join at Punakha to form the Puna Tsang Chu. Both of these tributaries have their source in the glaciers and glacial lakes in the northern part of the country. Further downstream at Wangduephodrang, the river is joined by another tributary called the Dang Chu which has it source mainly from the collection of mountain streams further up the Sha Valley.

Status of Glaciers in the Headwaters of the Puna Tsang Chu

As already mentioned in the previous section, there are quite a number of glaciers and glacial lakes present in the Puna Tsang Chu river basin where our DGM-NCAP project has been implemented. Considering the high sensitivity of glacial environments to any changes in the climate system it is important to know what is really happening to these glaciers and the lakes in the headwaters of the Puna Tsang Chu. The results from our earlier studies and observations are discussed in the following section.

Glaciers in the Himalayas are of two types based on their formation and whether they are clean type (C-type) or debris covered (D-type) glaciers. The Himalayan glaciers are also classified as "summer accumulation" types. The D-type glaciers are considered less sensitive to climate change since they have a mantle of debris deposited on their surface. On the other hand the C-type glaciers with their clean surface are considered to be quite sensitive to any changes in the climate, especially the temperature.

A ground survey was conducted on a C-type Jichu Dramo glacier, a small clean type glacier in the same basin in the Bhutan Himalayas as a part of field activities under the joint Japan-Bhutan research project in 1998 and resurveyed in 1999 to assess the changes. The results and the work details reported a 12m retreat (from 1998 to 1999) with a rough estimation of 2 to 3m in surface lowering.

The retreat rates for the C-type glacier in the Bhutan Himalayas were compared with the retreat rates for some of the glaciers from east Nepal. The result was that the retreat rates are higher for the glaciers in the Bhutan Himalayas than the glaciers in east Nepal, which confirms the sensitive nature of glaciers to the intensity of the monsoon.

In addition to the retreat rate the authors also computed aerial shrinkage for 66 C-type glaciers in the Bhutan Himalayas for a period of 30 years. The glaciers occupied an area of 146.87km^2 in 1963 but this area decreased to 134.94km^2 by 1993. This is about 8.1% aerial shrinkage within a time span of just 30 years.

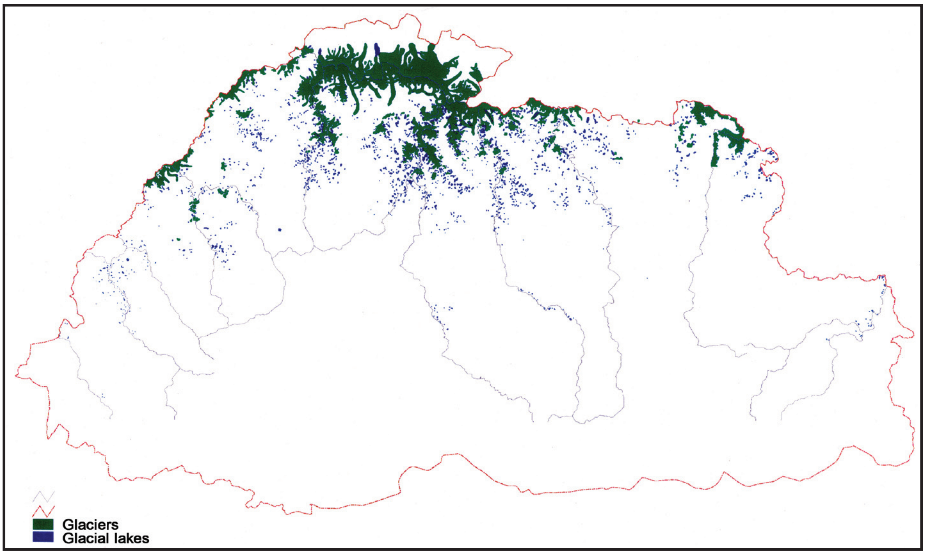

Figure 5: Glaciers and Glacial Lakes in the Bhutan Himalayas

Status of Glacial Lakes in the Puna Tsang Chu River Basin

Numerous studies were conducted on the glacial lakes in Bhutan from 1998 to 2004 during the joint Japan-Bhutan and joint Austria-Bhutan projects in Bhutan. In connection with these studies many scientific articles were published in relation to risk associated with those lakes, mechanism of lake expansion and stability of the lakes, some of which are already cited in the previous sections.

This section gives different scenarios regarding lake expansion both from the earlier works by different experts and results from present work. The discussions are mainly focused on the lakes in two sub-basins namely Pho Chu and Chamkhar Chu sub-basins due to availability of data for comparison and presence of major lakes.

The first detailed work on the expansion of glacial lakes in Bhutan was the work by Professor Yutaka Ageta from Nagoya University Japan with time series sketches of major glacial lakes in

Lunana region in Bhutan Himalayas. In his subsequent study the evolution of a number of lakes was discussed in detail by using maps, photographs and satellite images[2]. Risk of the outburst in relation to the geophysical environment in and around those lakes were also incorporated in his work.

Ageta then examined the rate of retreat on some selected large D-type glaciers associated with large lakes by comparing past photographs, satellite images and maps of different years. Basically applying the concept of lake expansion rate up valley with the corresponding retreat rate for the related glaciers, the authors reported retreat rate in the range of 30 to 35m/year. However the rates were found to be variable with time which was mainly attributed to irregular calving process at the tongue of the mother glacier which is in contact with the lake water.

Luggye Lake

Figure 6 shows the evolution of Luggye Lake from the late 1950s to 1994 and it measured 142m in depth in 2000. The reduction in the surface area in 1994 was due to GLOFs in October 1994. The only risk associated with GLOFs from Luggye Lake in the future could be due to the outlet being blocked by landslides from the left lateral moraine at the outlet causing a rise in the water level of the lake. If ever such a GLOF occurs in future, this will have a serious impact on the Thorthormi Lakes further downstream considering the already weakened left lateral moraine of the Thorthormi glacier.

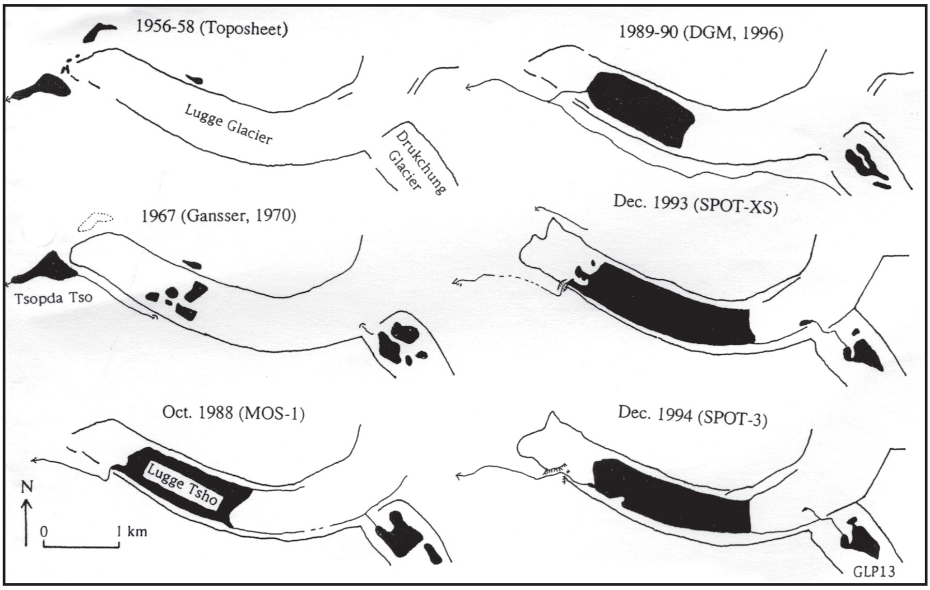

Figure 6: Expansion of Luggye Tso

Similar comment on the risk from Luggye Tso has been reported by the Austrian experts. In fact there were five possibilities proposed during the risk assessment of the Luggye GLOF, as to which outlet being blocked by landslides from left lateral moraine was considered as 'major risk'. Therefore, their recommendation was to stabilize the active sliding zone on the left lateral moraine at the Luggye outlet to allow free flow of water from the lake.

2 The following lakes were studied: Luggye glacial lake, Raphstreng glacial lake, Thorthormi supra-glacial lakes, Tarina lakes and Chubda Tso.

On the contrary, Yeshi Dorji from the Geological Survey of Bhutan observed no immediate GLOF risk from this lake considering the wide outlet channel. He commented that 'the risk of flood from this lake is not there right at the moment as the outlet channel is wide enough to allow any amount of water that will accumulate'.

Raphstreng Lake

Figure 7 shows the expansion of Raphstreng Lake from the late 1950s to 1994 and it measured about 100m in depth in 1999. The present dimension of the lake is believed to be at the end of its expansion since the upstream part has already reached the bedrock wall. Though three phases of mitigation work were carried out on this lake from 1996 to 1998 lowering the lake water level by about 4m, the risk of GLOF still cannot be ruled out considering the large volume of water still stored in the lake and chain effect of GLOF from other adjacent lakes. The building up of hydrostatic pressure in the adjacent Thorthormi lakes, which only have moraine walls as a barrier between them poses a threat to the stability of the Raphstreng Tso.

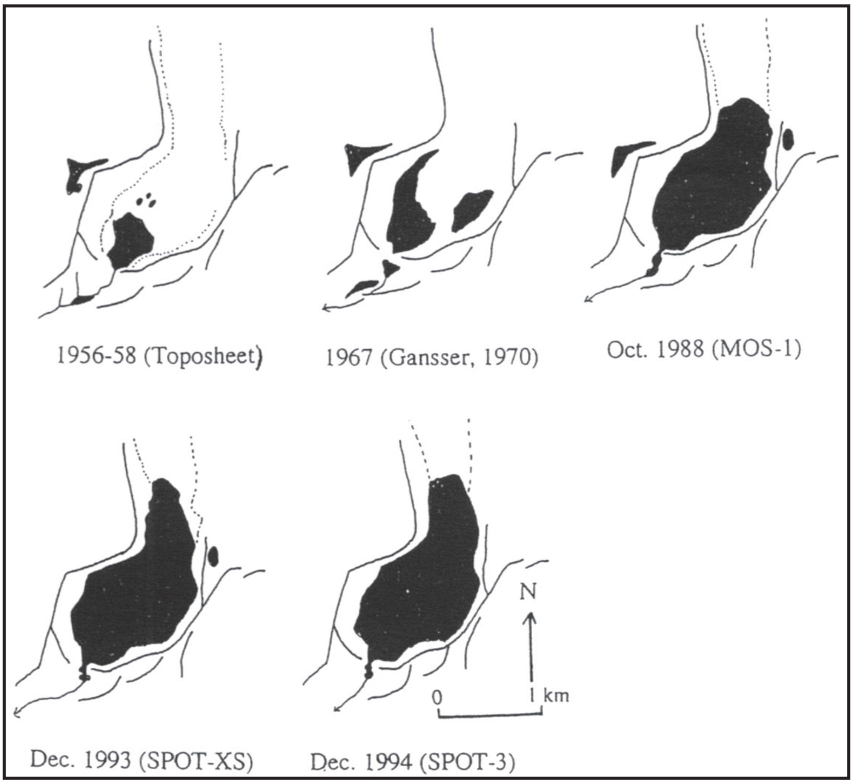

Figure 7: Expansion of Raphstreng Tso

Thorthormi Lakes

Figure 8 shows a time series expansion of the Thorthormi Lakes from 1956/58 to 1993. Ageta reported supra-glacial lakes on this huge debris covered glacier in the 1990s. A continuing expansion of these supra-glacial lakes was seen in 1998 during the first joint Japan-Bhutan field expedition. Considering the accelerated ice melt, gentle gradient at the snout region, eroding of the left lateral moraine ridge by discharge water from Luggye Lake in the upstream and seepage from the left lateral moraine, it was concluded that this growing lake has the potential for outburst in the near future.

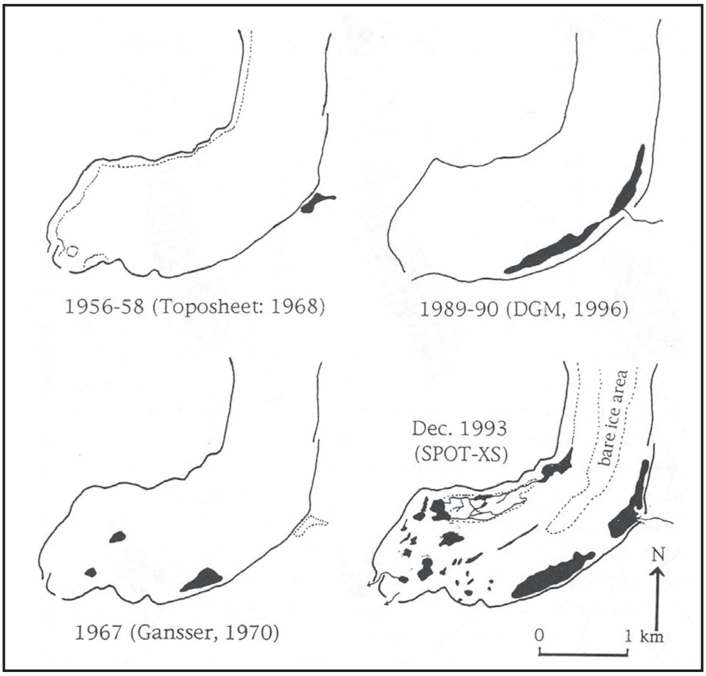

Figure 8: Expansion of Thorthormi Tso

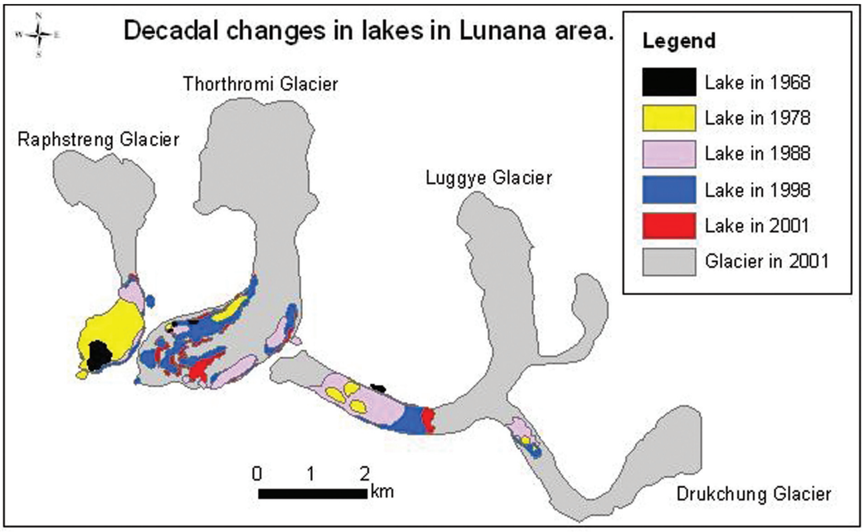

Figure 9: Decadal changes of lakes in the Lunana complex.

An attempt has been made to map the changes of the glacial lakes in the Lunana area on a decadal base from 1968 to 2001 in terms of both area and length (figure 9).

All the three major lakes (Raphstreng, Thorthormi and Luggye) show a sudden increase in surface area and it is clear that all the lakes except for Raphstreng are still expanding and show an expansion pattern.

Potentially Dangerous Lakes in the Puna Tsang Chu River Basin

24 potentially dangerous lakes were identified during the last inventory work based on a set of criteria such as rise of lake water level, associated mother glacier, condition of dams and topographical features of surroundings. The base maps used for their identification were topographical maps from the 1960s. The Thorthormi Lakes were not significant then as no water bodies were detected on the mother glacier (Thorthormi glacier). But today as shown in the previous section the Thorthormi Lakes are considered to be some of the critically dangerous lakes in the Bhutan Himalayas considering their expansion rate and the unstable moraine dam surrounding it. Therefore, the total number of potentially dangerous lakes in the Bhutan Himalayas at present is 25 with the inclusion of the Thorthormi Lakes.

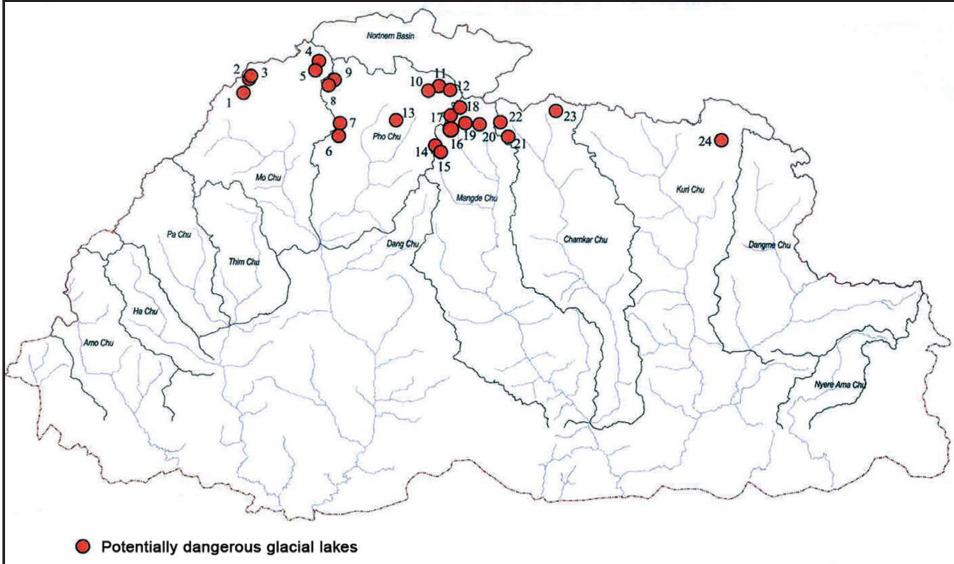

Figure 10: Location of potentially dangerous glacial lakes in the Bhutan Himalayas

The above figure (figure 10) shows the location of potentially dangerous lakes in the Bhutan Himalayas. Out of 25 potentially dangerous lakes, 5 lakes were found at the source of the Mo Chu and 9 lakes were located at the source of the Pho Chu. Therefore a total of 14 potentially dangerous lakes were identified in the Puna Tsang Chu River basin which accounts for 56% of the total potentially dangerous lakes.

Hazard Zones

A hazard is a phenomenon that may adversely affect human life, property, activity or the environment to the extent of causing a disaster. In our context GLOFs from the combination of two potentially dangerous glacial lakes at the source of the Pho Chu are the hazard and we have tried to zone the areas along the Puna Tsang Chu into different levels of hazard from GLOFs. The three hazard zones (red, yellow and blue) identified in this project represent three different hazard levels as outlined below in the table. The technical details and steps involved in the delineation of these different hazard zones are given in the methodology section.

Most of the areas both inhabited and uninhabited along the Puna Tsang Chu from Khuruthang in Punakha to Lhamoizingkha on the Bhutan-India border under Dagana *Dzongkhag* have been covered by this project.

Table 1: Different Levels of Hazard

Hazard Level	Map Color	Descriptions
High	Red	Persons are in danger both inside and outside their houses. Structures are in danger of being destroyed.
Medium	Yellow	Persons are in danger outside their houses. Buildings may suffer damage and possible destruction depending on construction characteristics.
Low	Blue	Danger to persons is low or non-existent. Buildings may suffer little damages.

Red Zone (Prohibited Zone): Represents the area that would be under water in case of worst case scenario GLOF occurrence. All structures in this area would be affected by flood.

Yellow Zone (Regulation Zone): Represents the areas that would be impacted indirectly by the worst case scenario GLOF. Therefore, the existing structures need to be reinforced and future development should be planned accordingly.

Blue Zone (Regulation Zone): Represents the areas that are safe from the worst case scenario GLOF.

Vulnerability Assessments

Vulnerability can be defined as a condition resulting from physical, social, economic and environmental factors or processes which increase the susceptibility of a community to the impacts of a hazard. The IPCC defines vulnerability in relation to the impacts of climate change and it 'is the extent to which a natural or social system is susceptible to sustaining damage from climate change'. In our context it is the degree of risk of GLOF along the Puna Tsang Chu on the lives, property and infrastructure located on either side of this river.

Vulnerability assessment is a way of establishing who is vulnerable, where they are and what the strategies to combat vulnerability are. It is significant for current and future planning exercises for proper risk management, preparedness and critical decision making which are all essential if the most vulnerable people are to be given the assistance they need.

Accordingly, under this section we have tried to compile the details of different sectors which are likely to be impacted based on worst case scenario GLOF in the future. To be more specific and informative we have concentrated more on the areas which have infrastructure and settlements for which the details are given below.

Conclusion

Table 2: Summary of vulnerability assessment in the project area

Hazard Level	Map Color	No. of Buildings	No. of People	No. of Live-stock	Historical Monuments	No. of Bridges	Road Length (Km)
Low	Red	117	362	28	16	01	5.22
Medium	Yellow	173	836	220	06	06	8.64
Low	Blue	669	1781	1072	04	00	39.92

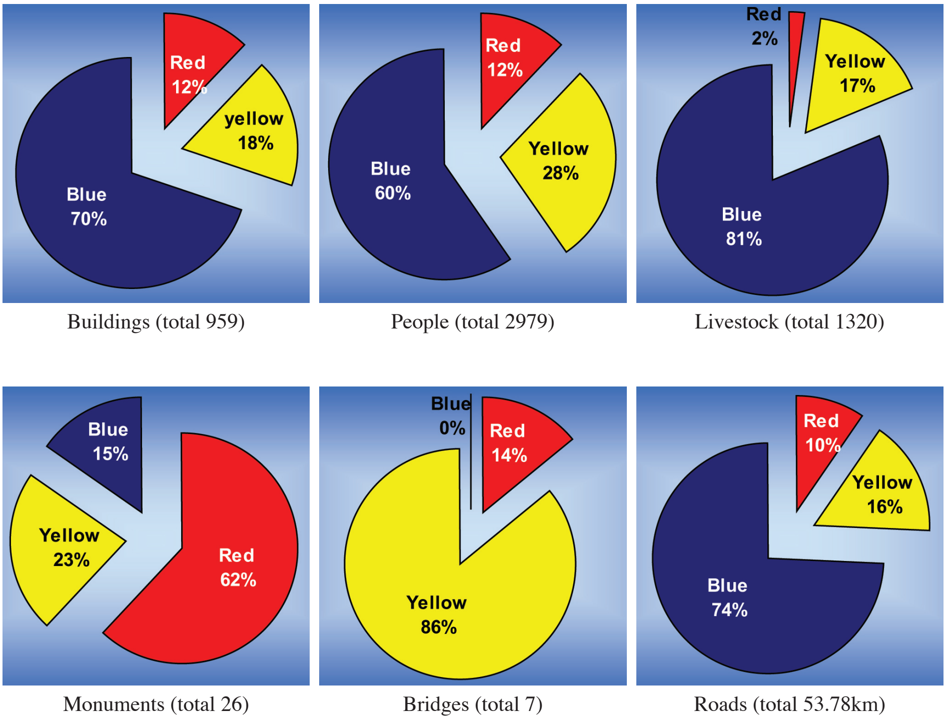

Figure 11: Percentage of socio-economic assets and infrastructure in different levels of hazard for the whole project area.

Table 2 shows the summary of vulnerability assessment in the whole project area.

Figure 11 shows the percentage distribution of different socio-economic assets and infrastructure, which falls in different level of hazards if GLOF occurs along the Puna Tsang Chu. The details of individual vulnerable communities and infrastructure are given in the diagram.

Table 3 shows the areas of different land use in different levels of hazard along the Puna Tsang Chu.

Table 3: Different land use in different hazard levels in the project area.

Hazard Level	Map Color	Cultivated Land (Km)	Arid Land (Barren, Open, Scrubs (Km)	Forest Cover (Km)	Built Up Area (Km)	Orchard (Km)	Total (Km)
High	Red	0.411	1.084	2.586	0.106	0.022	4.239
Medium	Yellow	1.330	1.134	2.585	0.193	.136	5.378
Low	Blue	5.882	7.988	26.378	1.797	0.308	42.534

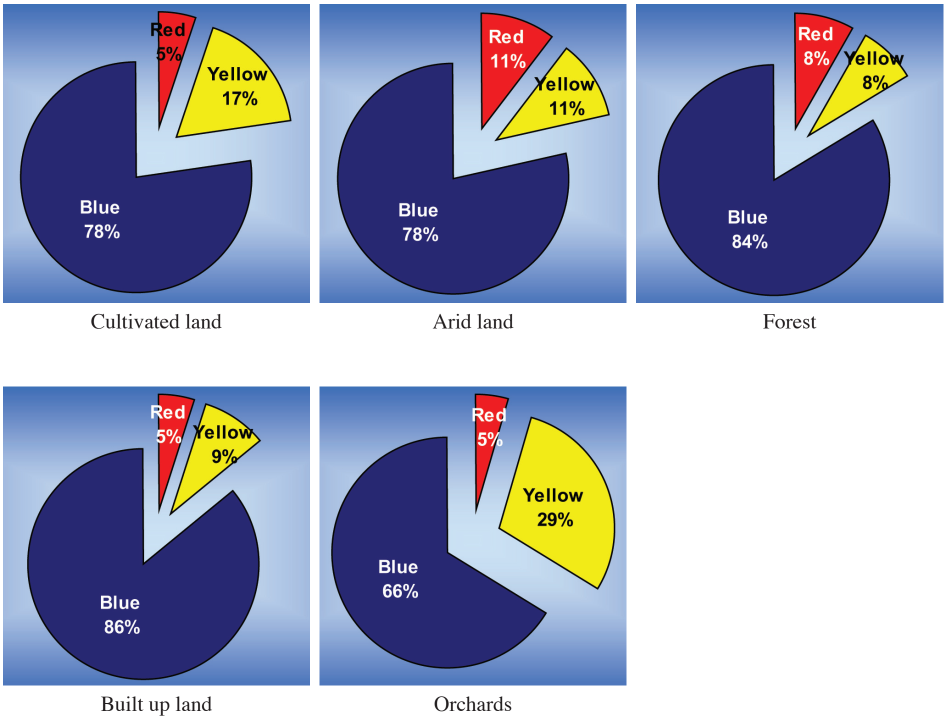

Figure 12: Percentage of different land use in different hazard levels for the project area.

Since any kind of flood will have a devastating effect on the land use type along its course it is imperative to make an assessment on the vulnerability of land use along the Puna Tsang Chu for future GLOF scenarios. Figure 12 shows the percentage of different land use in different hazard levels for the entire area of the project area.

Conclusions and Recommendations

The main output from this project is the hazard and vulnerability maps for GLOFs along the Puna Tsang Chu from Khuruthang to Lhamoizingkha at the Bhutan-India border. These maps can be used for future planning of various developmental activities and as a tool for better decision-making by concerned authorities. This project identified the areas along the Puna Tsang Chu with different level of hazards of GLOF. As a main recommendation for future projects, it is suggested to identify a safe area for each community selected in this project. This sort of study will require a series of data and an entirely different working methodology for delineating a safe zone area for evacuation purpose during the time of GLOF in the future.