Glacial Lake Outburst Flood (GLOF) Hazard Mitigation at Himalayan Region, Nepal

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Abstract

Glacier retreat is a strong indicator of climate change and global warming. The anthropogenic changes in the Earth's atmosphere are mostly to blame for the climate extremes and their consequences in the last few decades. The Himalayan region is no exclusion to the trend. As glaciers begin to retreat, the glacial lake starts to fill or form behind the natural moraine or ice dam in the glaciers. The sudden release of the water, known as the Glacial Lake Outburst Flood (GLOF), can release a large amount of water and sediment. There have been various destructive GLOFs recorded in Nepal since the 1960s. It is vital to understand the GLOF dynamics, geomorphology and historical events to mitigate the GLOF hazards in the region. An advanced approach based on remote sensing data and empirical evidence is more suitable to tackle these issues.

This research investigated 11 among 30 past events recorded in the HKH region (Nepal) to establish the causes and triggering factors that led to the catastrophic failure, which helped establish the vulnerability assessment of these glacial lakes. This eventually led to creating a GLOF vulnerability assessment framework that is unique and useful to the communities. This research concluded that 40% of the GLOF events was due to the moraine dam failure. In the retrospective approach, 5 out of 11 glacial lakes scored a very high total vulnerability score (TVR), which suffered catastrophic events in the past. The TVR of the currently existing 21 potential dangerous glacial lakes (PDGL) in Nepal was also conducted using the proposed assessment framework that concluded the 7 very high, 4 high, 5 medium, and the rest are low. Hence, this assessment tool's reliability is very high. This research also concluded that there should integrated approach to climate change adaptation and hazard mitigations in the region.

Publication related to this thesis

Parts of this research have been published or submitted to the following peer-reviewed publications and international conference proceedings.

- **Sedai, S.,** Jayaratne, R. and Acharya Nepal, J. (2021). Himalayan Glacial Lake Volume and Potential Glacial Lake Outburst Flood (GLOF) Discharge Calculation. In: *6th SONEUK Conference*. [online] Shiva Sedai. London: Society of Nepalese Engineers in UK, pp.39–45. Available at: http://www.soneuk.org/wp-content/uploads/2021/07/6th-SONEUK-Conference-Proceedings-2021.pdf [Accessed 27 Sep. 2021].

- Sedai, S., Jayaratne, R., Nepal, J., Abdalla, H. and Grant, D. (2018). *Glacial Lake Outburst Flood (GLOF) Triggering Factors at Hindu Kush-Himalaya, Mt. Everest Region, Nepal*. [online] agu.confex.com. Available at: https://agu.confex.com/agu/fm18/prelim.cgi/Paper/421670 [Accessed 7 Jun. 2021].

- **Sedai, S.,** Jayaratne, R., Grant, D. and Nepal, J. (2018). Glacier Hazard Mitigation at Hindu Kush Himalaya Region through Numerical and Hydrological Modelling. *The Young Researchers' Conference 2018*. [Online] London: Institution of Structural Engineers, pp.84-85. Available at: https://www.istructe.org/events-awards/conference-and-lectures/young- researchers-conference.

- **Sedai, S.,** Jayaratne, R., Grant, D. and Nepal, J. (2018). Failure Mechanism of Moraine-dam at the Himalaya Glacial Lake, Nepal. *Research & Knowledge Transfer Conference 2018.* [Online] London: University of East London. Available at: https://www.uel.ac.uk/events/2018/06/research-and-knowledge-exchange-conference.

- **Sedai, S.,** Jayaratne, R., Grant, D. and Nepal, J. (2017). Glacial Lake Outburst Flood (GLOF): Process Chain Modelling, *UEL Research & Knowledge Transfer Conference 2017,* London.

Table of Contents

List of Figures

List of Tables

Nomenclature

Roman Symbols

A	Cross-section of the area
A_G	Area of the host glacier
A_L	Area of the lake
B	Riverbed width
c_*	Sediment concentration of the underlying sediment bed
$\bar{c}$	Depth-averaged and volumetric sediment concentration
D	Distance between glacial lake and terminus
d	Particle diameter
d	Particle size diameter
E	Erosion rate of the bed sediment
e	Restitution coefficient
f	Friction factor
g	Acceleration due to gravity
h	Flow depth
q	Inflow per unit area
Q	Discharge
Q_s	Sediment discharge
R	Rainfall
S	Seismic events
S_D	Mean slope of the moraine dam
S_f	Friction slope
S_L	Slope between glacial lake and glacier terminus
t	Time
$\bar{u}$	Depth-averaged velocity of the mixture
V	Velocity
x	Distance along the channel
z	Elevation

Greek Symbols

$\bar{\rho}_m$	Depth-averaged mass density of the sediment–water mixture
σ	Mass density of the sediment particle
ρ	Mass density of water including fine sediment
τ_b	Bed shear stress
z_b	Bed elevation from a reference level respectively
θ	Bed slope
β	Momentum-correction factor
τ_y	Yield stress due to particle-to-particle contacts
θ_e	Equilibrium bed slope corresponding to the sediment concentration
$\emptyset_s$	Inter-particle friction angle of sediment particles

Abbreviations

1D	One-Dimensional Space
2D	Two-Dimensional Space
AHP	Analytical Hierarchy Process
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
CBEWS	Community Based Early Warning System
CFGORRP	Community Based Flood and Glacial Lake Outburst Risk Reduction
DEM	Digital Elevation Model
DHM	Department of Hydrology and Meteorology
FA	First Aid
GIS	Geographic Information Systems
GISS	Goddard Institute for Space Studies
GL	Glacial Lake
GLOF	Glacial Lake Outburst Flood
GRMCC	GLOF Risk Management Coordination Committee
HDI	Human Development Index
HEC-RAS	Hydrologic Engineering Centre's River Analysis System
HKH	Hindu Kush Himalayan
ICIMOD	International Centre for Integrated Mountain Development
IPCC	Intergovernmental Panel on Climate Change
LDC	Least Developed Countries
LIA	Little Ice Age
MBT	Main Boundary Thrust
NASA	National Aeronautics and Space Administration
NDWI	Normalized Difference Water Index
PDGL	Potential Dangerous Glacial Lakes Project
PFV	Potential flood volume
QGIS	Quantum Geographic Information Systems
RGSL	Reynold Geo-Science Ltd, UK
SRTM	Shuttle Radar Topography Mission
TVS	Total Vulnerability Score

UNFCCC	United Nations Framework Convention on Climate Change
UNISDR	United Nations International Strategy for Disaster Reduction
USGS	United States Geological Survey
WGMS	World Glacier Monitoring Service
WHO	World Health Organization
WWF	World Wide Fund

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Dedication

Punna Maya Sedai, our beloved grandmother, who is still taking care of me from the distant star. I see you every night, *hajur'aama*!

Chapter 1

1 Introduction

Snow melting and glacier retreating are the most visible indicator of climate change. Thinning and retreating of these glaciers over the past century has led to the creation and progression of glacial lakes at the margins of glaciers and moraines in all high mountain regions of the world (IPCC, 2014), particularly at Hindu Kush-Himalaya (HKH) region. The continuous expansion of these glacial lakes poses a high risk of Glacial Lake Outburst Flood (GLOF). These can release millions of cubic meters of water in a short period and produce floods (debris flow, flash flooding) with high peak discharges and extraordinary erosive and transport capacity (Breien et al., 2008). Therefore, it is essential to study glaciers' present status and their associated glacial lakes and surroundings to understand the temporal and spatial changes of such glaciers, glacial lakes, and forecast future worst-case scenarios.

However, it is very challenging to obtain an accurate spatial extent of the glacial lakes including length, width and depth, and the rate at which they change the shape due to an extreme weather condition of the Himalaya, hence field investigation is not feasible all the time. So, remote sensing is considered the best way to investigate glacial lakes and the impact of GLOFs in the remote glacier mountainous region (Bolch et al., 2008). This research aims to devolve a comprehensive framework to understand glacial lake vulnerability and thereby access the future changes.

More than 30 GLOF events (Fig. 1.1) were recorded in the Hindu Kush Himalaya region since 1930. Among them 14 GLOF events affected Nepal. This research investigates only 11 of them, which can be precisely located and mapped. In the Himalayas, data about failed glacial lakes have not been systematically analyzed yet, especially the mechanism of moraine-dammed glacial lake failure and its contributing factors which remain mostly unknown. This research analyses the data collected by extensive literature review and satellite data (Landsat) to identify the common cause of GLOFs in the high Himalaya region (Fig. 1.1). Remote sensing techniques are particularly suitable for this task allowing rapid analysis of the large glaciated region (Huggel et al., 2002). It will also provide significant resources to study the remote area's geomorphology, particularly these high Himalayan glacial lakes and build a comprehensive framework to carry out the vulnerability assessment of glacial lakes and improve community resilience.

It is vital to understand the GLOF dynamics; hydrodynamic characteristics (discharge and flow behaviour), causes or GLOF triggering mechanisms (dam overtopping, seepage, any mass movement, earthquake, temperature rise, surge wave, ice melting) of the GLOFs will help to dynamics to mitigate the potential GLOF hazard in the region. This research will explore the 1998's Tam Pokhari GLOF, that occurred in Dudh Koshi basin, Nepal which destroyed property, with an estimated cost of US$ 2 million and many lives were lost (Dwivedi et al., 1999). This will help to put the mitigation measure in place. Dealing with changing climate and reducing the anthropogenic reason for global warming is a shared responsibility. Focusing on climate change adaptation and opting for the more sustainable solution will help build a more resilient community.

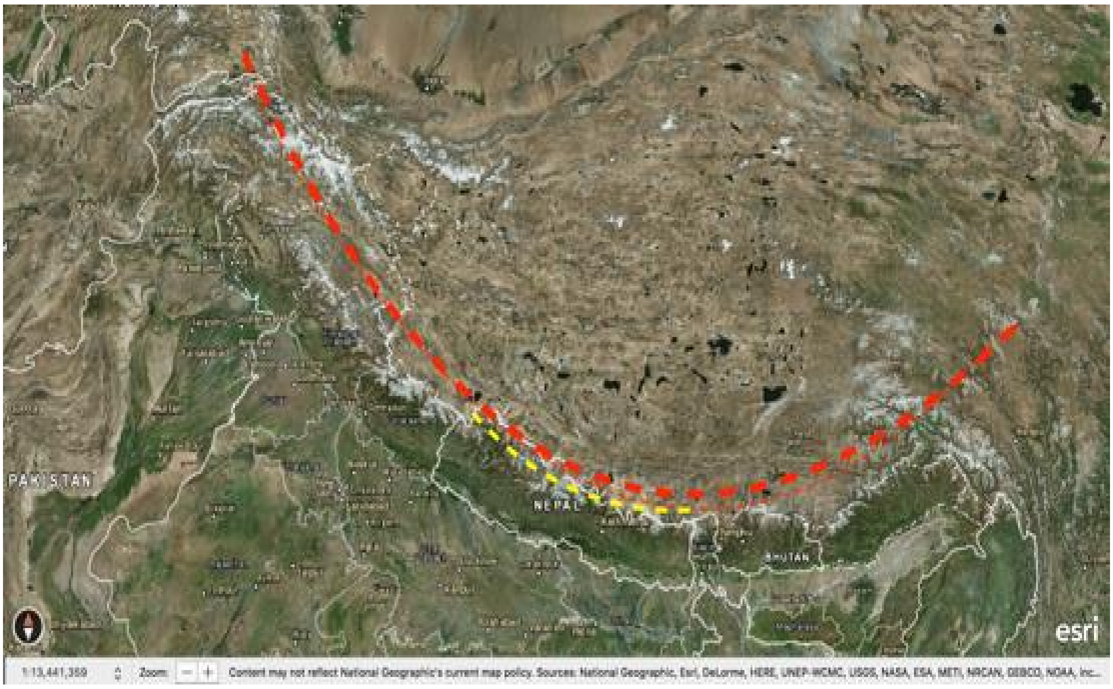

Figure 1.1 HKH Region (Red), Nepal Himalaya Yellow (Google Earth, 2018)

1.2 Background of the study

High mountain glacier has been retreating at alarming rates since the latter half of the twentieth century due to climate change and global warming. As a consequence, the Himalaya region is a critical contributor to potential natural hazards, particularly glacial lake outburst floods (GLOFs). Catastrophic floods due to the outburst of glacial lakes have been recognized as one of Nepal's primary natural hazards, making downstream areas vulnerable. GLOF is a dynamic process as it involves the occurrence of a complex phenomenon. It differs from place to place depending on the area's geomorphological setting, lake geometry, dam material, and other external factors (e.g., earthquake, heavy precipitation). Monsoon rainfall commonly triggers various slope movements, many of which cause extensive damage to life and property. Most of these events are not adequately documented due to various reasons including the remoteness of the location, inability to access modern technology and other socio-political reasons.

Several catastrophic GLOF events in Nepal destroyed expensive mountainous infrastructure, resulting in loss of life, property and hydropower project. One example is the 1985 event at Dudh Koshi basin that destroyed hydropower infrastructure and 14 bridges and many lives (ICIMOD, 2010). The recent recorded GLOF event was at Tam Pokhari GLOF 1998. It has been reported that some GLOF had long-term environmental degradation with socio-economic impact locally and downstream floodplain in the neighboring country when it happens to be on a border (Ives, 1986). Hence, it is a transborder issue, requiring multiple stakeholders to solve the issues. To date, there have been 24 GLOF events identified in Nepal in which 14 of them were originated in Nepal. The rest originated in Tibet, China but harmed both sides of the floodplain. (Bajracharya et al., 2007; Ives et al., 2010). On average, in the Himalayan region, at least one GLOF is recorded every three to ten years (ICIMOD, 2011).

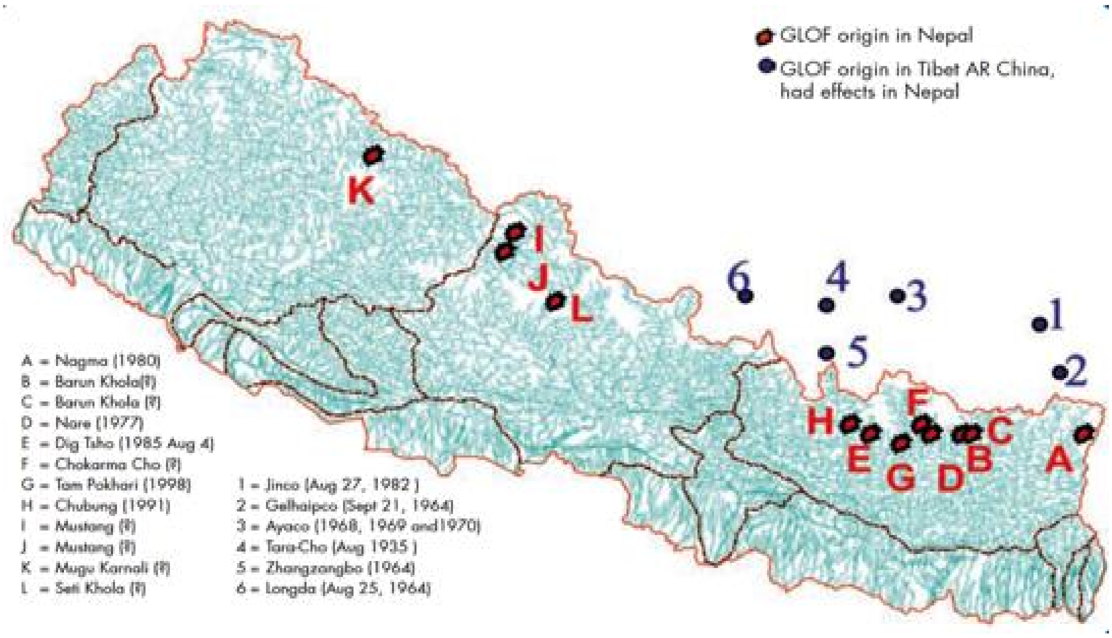

Figure 1.2 GLOF events affected Nepal (ICIMOD, 2010)

1.3 Knowledge gap and problem statements

The glacial lake's sudden release of the water with high transport and erosion capacity (Breien et al., 2008) is known as the glacial lake outburst flood (GLOF). Often it is associated with debris flow (Duckson and Duckson, 2001) with maximum discharge exceeding 104 m^3 s^{-1} (Costa and Schuster, 1988), while debris volume may exceed millions of cubic meters (Hubbard et al., 2005). It has been studied around the world with different perspectives, including the Himalayan region (Yamada, 2000; Quincey et al., 2007; Bajracharya et al., 2007), European Alps (Huggel et al., 2002), British Columbia (Kershaw, Clague and Evans, 2005) Scandinavia (Breien et al., 2008), Hindu Kush (Iturrizaga, 2005; Ives, Shrestha and Mool, 2010), Tian Shan (Narama et al., 2010; Bolch et al., 2011), Pamir (Mergili and Schneider, 2011), Peruvian Andes (Carey et al., 2012).

The instability of the natural (moraine/rock/dead ice) dam may cause by various slope movements into the lake and surrounding such as icefalls, rockfalls, or landslides (e.g., Costa and Schuster, 1988; Jiang, Cui and Jiang, 2004). Other external factors such as earthquakes (Lliboutry et al., 1977; Clague and Evans, 2000), intense rainfall (Yamada, 1998), ice cores melting in moraine dam (Richardson and Reynolds, 2000b), natural outflow channels blockage and the downstream flood wave propagation at downstream (Vilımek et al., 2005). Self-destruction also may be the cause (Yamada, 1998). The likelihood of the different natural dam stability parameters and triggering factors has to be included in hazard assessment according to their geomorphology. This is lacking at present from the Himalayan glacial lakes. The debris flow associate with GOF has posed a significant threat to the high mountain region. Due to the remoteness of the location, it is very challenging to conduct the field investigation and collect related data set; hence remote sensing could be a suitable option.

Moreover, advancement of the modern technology could help to save time and valuable resources. This phenomenon needs thorough investigation in order to mitigate the potential hazard in the region. It is, therefore, necessary to establish the vulnerability of the glacial lakes by accessing their stability parameters and stability factors. Once the glacial lake's vulnerability is determined, to mitigate the GLOF hazard in the region, the climate change adaption strategies should be identified. Making any changes toward current and predicted climate to reduce the potentional harm can be defined as climate change adaptation.

There is more research need to be done to identify the effective practices and processes of climate change adaptation (Pfister, 2010) and empirically grounded research can give more insight to adaptive capacity and the theories behind it. This will also help to identify why such adaptive policy worked (or does not work) and what are the obstructing and facilitating factors for implementations. Disaster risk reduction and climate change adaptation should be approached as interdisciplinary to be most effective, there by producing holistic approach to hazard management and adaptations (Birkmann and Teichman, 2010). Technological advancements, engineering innovation and decision-making process should integrate to solve these issues. To identify and improve the disaster risk reduction and climate change adaptation strategies, it is very important to learn lessons from the actual events from the past that are influenced by the evolution of the natural hazard (Amendola et al., 2008).

1.4 Aim and Objectives

The aim of this study is to understand the present conditions of the glacier lakes and establish their vulnerability to mitigate GLOF hazard in the region based on their stability parameters and conditioning factors.

To meet the aim of this research, the study will focus on the following objectives:

- To understand the hydrological characteristics of the GLOF events in the Himalayan region, Nepal.
- To determine key GLOF occurring phenomena and causes of glacial lake failure in the Himalayan region, Nepal.
- To develop a comprehensive and novel glacial lake vulnerability assessment framework and access the vulnerability of the potential dangerous glacial lakes (PDGL) and establish their total vulnerability score (TVR) in region.
- To identify GLOF hazard mitigation and climate change adaptation strategies in the region.

1.5 The scope of the study

There is no comprehensive study of historical GLOF events on the Himalayan region, Nepal at present. This is one of the highly glaciated areas in the Hindu Kush Himalayan region and extremely susceptible to a frequent GLOF and related hazard. Several researchers have developed a different approach to assess glacial hazard including remote sensing, geographical information system (GIS), and statistical and empirical modelling (Huggel et al., 2003). However, these methodologies are developed to investigate a particular area of concern, e.g., Swiss Alps, British Columbia, and the Cordillera Blanca, Chile. Applicability of these methods to another region like Hindu Kush Himalaya Region warrants further studies and investigations due to the different geomorphological and weather conditions. Moreover, conditioning factor for GLOF plays a massive role in identifying the glacial hazard.

Hence, this research proposes investigating the cause of the historic moraine dam (natural dam) failure at Himalayan Glacier Lake and identifying the conditioning factor that led to catastrophic failure. Based on these findings, this research aims to build a comprehensive vulnerability assessment framework to carry out the vulnerability assessment of glacial lakes and improve community resilience in a relatively large and remote area. So, the proposed assessment framework will be inclusive and unique to the region, and engineers and planners can use this to access the associated risks to the infrastructure projects (dam, hydropower plant, road, school) in the region. This proposed framework can be used to other regions with similar geographical conditions but the component related to the weather conditions and seismic activities need to update accordingly.

1.6 Outline of Thesis

The thesis consists of seven chapters. The first chapter begins with an introduction, and other chapters are as follow:

Chapter 2 features the literature review of the study. Furthermore, in this section, climate change and its consequences to the Himalayan region are described. The history of GLOF at the Himalaya region Nepal and worldwide, has been explored along with its adverse effect on society and human settlement. The knowledge gap in GLOF risk assessment and disaster management was identified. The adaptation strategies for building a resilient society are also included.

Chapter 3 presents the hydrodynamic characteristics of the GLOF and downstream impact assessments due to the event being analysed using HEC-RAS 5.0.7. The 1998's GLOF events in Tam Pokhari GLOF is investigated in detail. Potential flood volume, maximum discharge, sediment transportation is examined and calculated. Erosion and sedimentation due to the GLOF in the downstream floodplain (V-shaped valley, U-shape valley) are discussed.

Further, an investigation of the past GLOF events in the study area is carried out in chapter 4. This is to determine the vulnerability and conditioning factors of the glacial lake, host glacier and surrounding area. Geomorphological parameters of the glacial lake, host glacier and surrounding area are extracted and analysed using satellite imagery, geographic information system (GIS) and analytical hierarchy process (AHP). The extreme weather events (rainfall) and seismic event in the area are also examined.

Chapter 5 developed the glacial lake vulnerability assessment framework, identifying potential GLOFs in the region. The critical value was assigned to different variables that have been determined in the previous chapter. This framework will help conduct the risk assessment of the glacial lake in the region and mountainous area worldwide. The retrospective assessment of the glacial lakes that suffered the GLOF disaster reveal that most of the glacial lakes were prone to disaster as most of them scored very high total vulnerability scores. Hence, the vulnerability assessment tool is reliable and effective. Furthermore, this assessment tool is used to conduct the vulnerability assessment of existing PDGL in Nepal. There are currently 21 PDGL in Nepal recognised by the government of Nepal and other research institutions including International Centre for Integrated Mountain Development (ICIMOD).

Chapter 6 explores how to manage GLOF disaster risk and climate change adaptation by improving community resilience. The GLOF formation mechanism is also discussed while past GLOF mitigation measure (Tsho Rolpa glacial lake risk reduction project, Imja lake lowering project) in the region is explored. Moreover, this chapter studied how climate change adaptation can be plausible to a community level by hardcore engineering solutions and soft solutions. The holistic approach to GLOF hazard mitigation is also concluded in this chapter.
Chapter 7 concludes the thesis while stating some recommendations and future work.

Throughout the project data collection, process and analysis have been carried out at different stages of the thesis as required; hence different methodologies have been adopted. Fig. 1.3 shows the overall methodology of the research project.

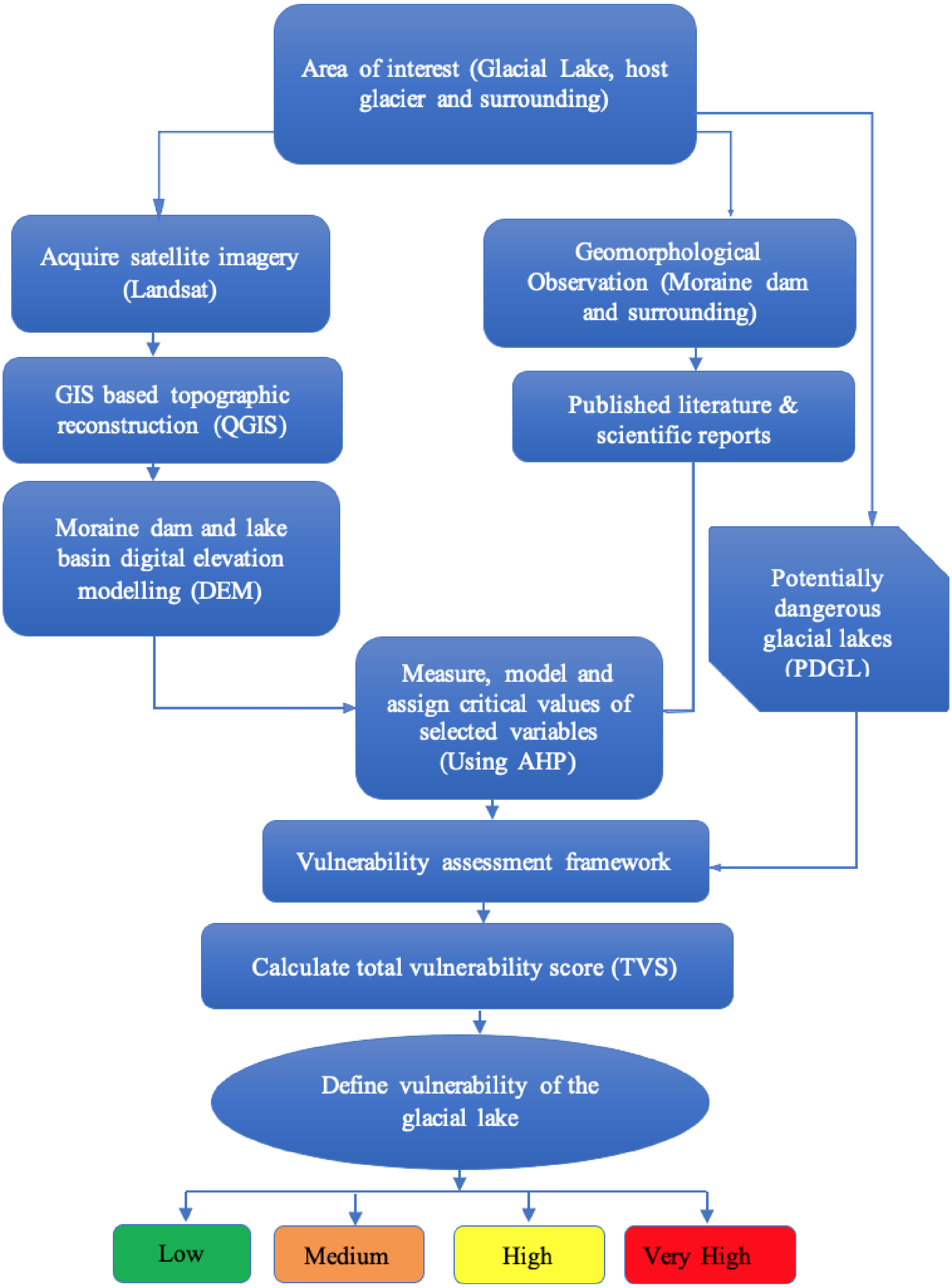

Figure 1.3 Vulnerability assessment framework; overall methodology

Chapter 2

Literature review

2.1 Introduction

In the Earth's five-billion-year-old history, the glacier variation and its condition due to the climate change are natural phenomena. Since then, this has been occurring, but since the last few decades, changing climate and global temperature rise constitute a significant hazard in a different part of the world, especially in the Himalaya region. The most significant hazards related to the glacier on these Himalaya are catastrophic drainage of glacial lakes. These floods caused by the breaking of natural moraine dams are known as glacial lake outburst floods (GLOFs). Due to the various anthropogenic and natural factor, continuous expansion of these glacial lakes poses a high risk of GLOF, which can release millions of cubic metres of water in a short period and produce floods (debris flow, flash flooding) with high peak discharges and extraordinary erosive and transport capacity (Breien et al., 2008). Therefore, it is essential to study glaciers' present status and their associated glacial lakes and surroundings to understand the temporal and spatial changes of such glaciers, glacial lakes, and forecast future worst-case scenarios.

The first comprehensive scientific study of the ice of glaciers was conducted by Agassiz et al., (1847), leading to the systemic monitoring at early nineteenth century (Haeberli et al., 2013). As knowledge and technology advance satellite-based virtual perspectives, including terrain information and imagery reveal the extent of the region's glacier changes. This has made it possible to get the remote location's geomorphological information, which otherwise would have been difficult if not impossible.

As glaciers recede in response to climatic warming, the number and volume of potentially hazardous moraine-dammed lakes in the Himalayas are increasing. These lakes develop behind unstable ice-cored moraines and have the potential to burst catastrophically, producing devastating GLOFs. With a large discharge (9500 m^3/s, Tam Pokhari GLOF, 1998), debris flows run a distance of more than 150 km (Osti and Egashira, 2010). Despite the scale of the risk, it is possible to assess and mitigate hazardous lakes successfully. Hazard assessment using satellite images has been practical for remote areas of Bhutan, and remediation techniques successfully developed in the Peruvian Andes are now being deployed in the Nepal. This research has developed a vulnerability assessment of the Himalayan glacial lakes based on remote sensing satellite imagery and empirical evidence to address this issue.

Figure 2.1 Early glaciologists at Unteraar Glacier, the large boulder serving as shelter on the medial moraine of Unteraar Glacier, Switzerland (Haeberli et al., 2013)

2.2 Glacier and Glacier mass balance

The glacier is a longstanding mass of ice sheet that moves slowly to the downhill. They are found at different parts of the world from higher mountains to the North and South pole. The formation of the process by which they shape the landscape is called glaciation. The glaciation occurs as climate conditions and topographic characteristics let snow accumulate over some years and transform slowly into firn (snow that persists for at least one year) and finally to ice.

The ice flows downstream (Fig. 2.1) due to the gravity with higher temperatures where different ablation processes, loss of snow, and ice dominate over the accumulation of snow and ice. The mass balance of the glacier depends on the sum of accumulation and ablation processes. In most of the region's accumulation occurs mainly due to solid precipitation (snow). However, accumulation also results from refreezing of liquid water, particularly at high altitudes where firn remains below melting temperature. On the other hand, ablation occurs mainly due to surface melting with successive runoff, but the ice loss by calving (in water or on land) or sublimation, mainly in dry regions can also dominate. Both accumulation and ablation can be affected by re-distribution of snow due to the wind and mass movements (avalanches). The mass fluxes and energy governing the surface mass balance is directly linked to atmospheric conditions, and they can be modified by various topography conditions including shading and steep slope. Glaciers adjust their size in response to climate changes (e.g., precipitation and temperature) and are therefore sensitive climate indicators.

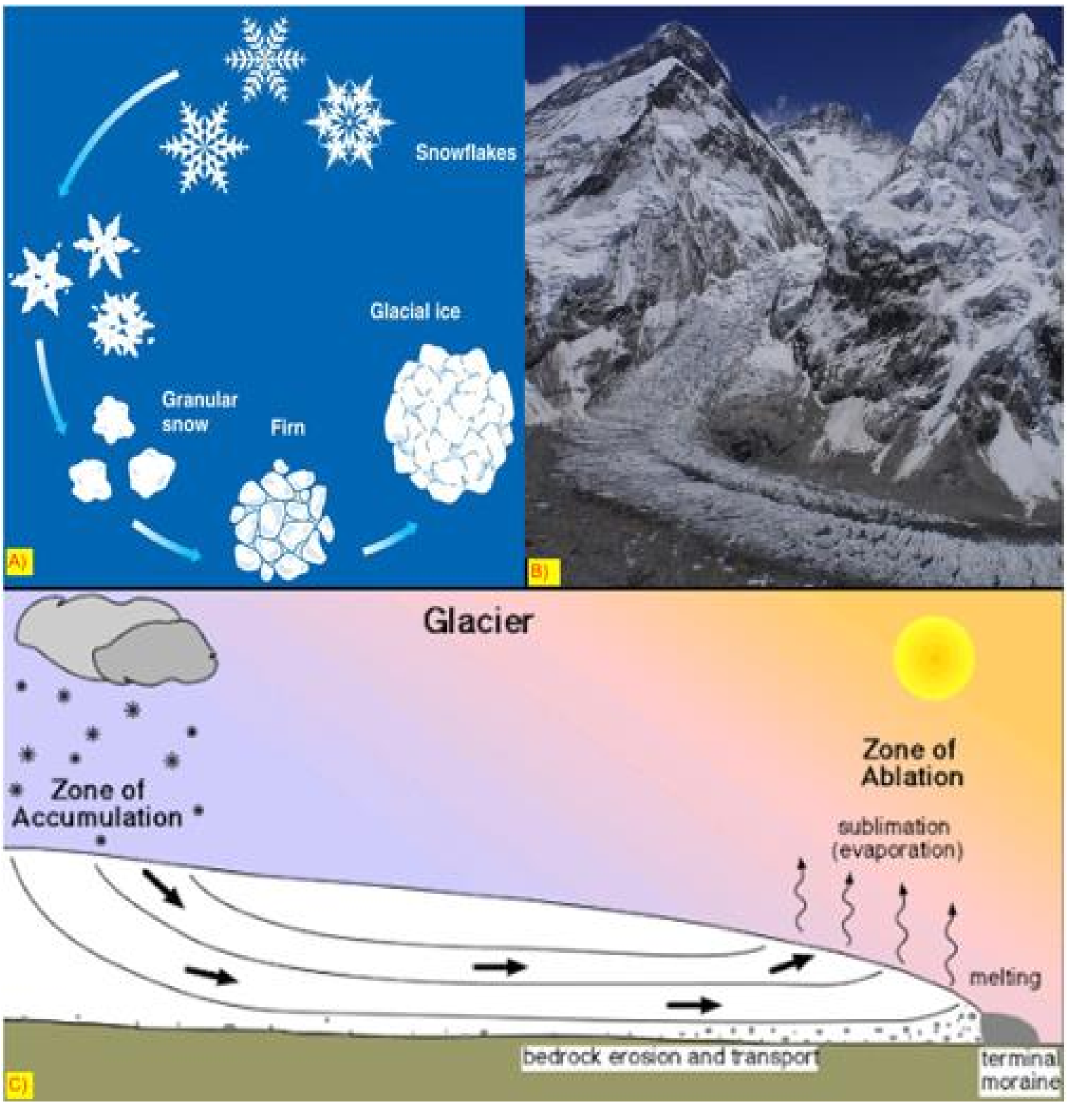

Figure 2.2 A) Glacial ice formation, B) Khumbu Glacier, Mt. Everest Region Nepal C) Schematic diagram of glacier formation (Glaciers, 2020)

Glacial mass balance is defined as being equivalent to the annual snowfall minus the annual snowmelt and the annual glacial ice melt from the glacier (Comeau et al., 2009). The melting of the glacier itself does not infer negative or positive mass of the glacier. In any hydrological year, positive or equilibrium mass balance can occur if snow accumulation is greater or equal than the ice and snow melt of the glacier. In contrast, negative mass balance of the glacier can happen if the volume of ice melt that exceeds the water is equivalent to the annual volume of snow accumulation into the system. This therefore affects an annual net loss of glacier volume. Glacial ice melting is a natural phenomenon. Mountain regions around the world including the HKH region, experience ice melt in their ablation zones. This contributes to the discharge of the mountain streams and rivers. A steady-state situation happens as climate conditions are such that glacial melt equals accumulation and there is no change in the mass balance over sometime. Glaciers are also important source for seasonal to long-term hydrologic reservoirs on a local and regional scale which is significant contributor to sea level rise on a global scale (IPCC, 2012).

The collection of information about ongoing glacier changes was initiated in 1894 with the foundation of the International Glacier Commission at the 6th International Geological Congress in Zurich, Switzerland. The long-term observation provides insight on how the climate is affecting the glacier retreat. Since this beginning of internationally coordinated systematic observations on glacier variations in 1894, a valuable and increasingly important data based on glacier changes was established. Currently, the World Glacier Monitoring Service (WGMS) collects standardized observations on changes in mass, volume, area and length of glaciers with respect to time (glacier fluctuations), and other details. The long-term observation series of the reference glacier's mass balance from around the world continues to be negative (Fig. 2.3). The data shows a continuous global pattern in strong ice loss over the past few years and brings the cumulative thickness loss (average) of the reference glaciers since 1980 at almost 20 metre water equivalents.

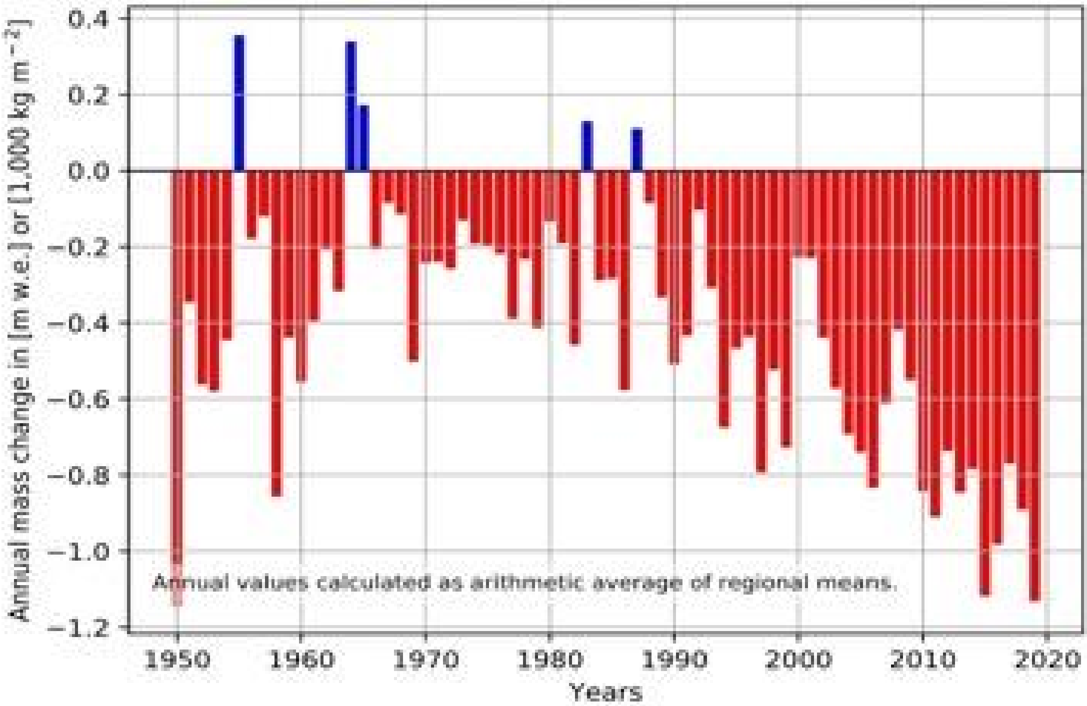

Figure 2.3 Annual mass balance of reference glaciers with more than 30 years of ongoing glaciological measurements between 1950-2019. Annual mass changes on x and y-axis in the unit metre water equivalent (m w.e.) which corresponds to 1000kg per square meter ($m^{2)}$ of ice (WGMS, 202).

2.3 Climate change and glacier recession

The large areas of snow and ice on the earth surface are close to melting conditions and therefore strongly react to changing climate. This fundamental principle has helped to identify the Quaternary ice ages and the related dramatic changes in climate and environmental conditions during the most recent part of Earth history. In this section observation and consequence of the climate change is examined.

Climate change can be defined as the long-term changes in the weather pattern of local and regional places (NASA, 2020). These changes can be observed in the different spectrum as effects on the planet and its consequences including temperature rise, change in precipitation, sea-level rise, mountain glacier melting, ice melting rates are faster in Greenland and artic. The earth's climate has been fluctuating over time, but the scientist has agreed that since the early 20th century, it is primarily driven by anthropogenic activities. The burning of fossil fuels helped increase heat-trapping greenhouse gasses (NASA, 2019), raising the temperature of the earth's surface. This is also referred to as global warming, which significantly contributes to glacial melting and sea-level rise.

Research on the rate of glacier retreat in the world's central mountain systems showed that the glaciers in the Himalayan region were retreating at a rate of 0.3 to 1 m per year, the highest among all regions (Dyurgerov and Meier 2005). Therefore, it is necessary to know the present status of these glaciers and the rate of continuous changes, which will also help predict future scenarios. In 2014, ICIMOD analysed Landsat, satellite images from around 2010 and identified 3,808 glacial lakes with area of 3,902 km^2 and average glacier was measured 1 km^2 in Nepal. The Ngojumba Glacier in the Dudh Koshi sub-basin, Nepal was the largest single glacier with 79 km^2 within the HKH region in Nepal.

2.3.1 Historical overview

In the northern hemisphere of Earth, consentient and polar ice sheets have developed and retreated many times in the past 3 billion years of Earth's history. This is due to the reduction of the earth surface temperature for an extended period of the time. The times with ice sheets are ice age or glacial period and time without large ice sheets interglacial period. Currently, the Earth is an interglacial period called Holocene. The last glacial period occurred between 120,000 and 11,500 years ago. Since then, Earth has been in an interglacial period. Mostly the glacial period is dustier, colder and drier than the interglacial time. These glacial-interglacial sequences are evident in different marine and terrestrial paleoclimate records from different parts of the world.

Due to variations in Earth's orbit over time the amount of solar radiation the Earth receives in each season has altered. The interglacial period lasts typically for about 10,000 years before the cooling or the next glaciation starts. This routine recurs at intervals of nearly 100,000 years (Denton and Hughes, 1983).

These glacial series are punctuated by comparatively short periods of localized cooling and warming, during which glaciers advance and retreat. In the current interglacial period, the most recent cooling episode generally referred to as the 'Little Ice Age' (LIA), affected parts of Asia (Chu Ko-Chan, 1973), Europe and North

America (Curry, 1969) from about 1300 AD over to the concluding half of the 19th century. Yamada et al. 1998 suggested that the glaciers were much longer during the LIA (1550-1850 AD). This may be due to volcanic eruptions and volcanic ash in the atmosphere, which caused cooling because it reduced the amount of solar radiation that reaches the surface of the Earth. Other changes also have been suggested including concentration of carbon dioxide in the atmosphere and tectonic activity.

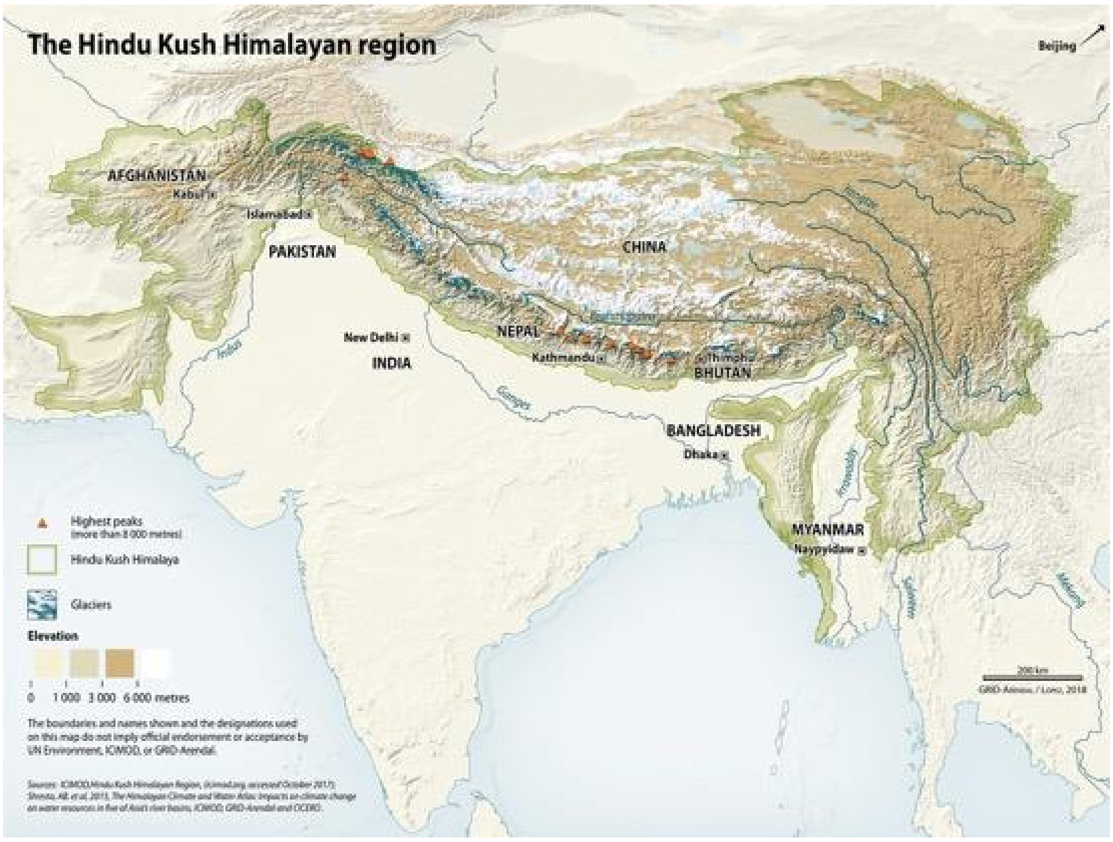

Figure 2.4 HKH Region (GRID-Arendal, 2018)

In Nepal, there is no comprehensive long-term observation of all glaciers until the present. However, there are some individual studies of several glaciers such as Khambu, Samba, Mera, Yala and Lirung. In 1956, Fritz Müller, a participant in the Swiss Everest Expedition, was the first scientist to visit Nepal since it opened to foreign scientists in 1950 (ICIMOD, 2011). The number of scientific expeditions has increased gradually since then. Higuchi led the first systematic field investigation of Nepal's glaciers in collaboration with The Nagoya and Kyoto Universities of Japan (Higuchi, 1976). The detail field study for AX010 glacier was conducted in 1978/79 (Ageta et al., 1980) while Samba and Yala glacier has been studied in 1947 and 1980s respectively (Fujita et al., 1997).

The International Centre for Integrated Mountain Development (ICIMOD) published the first inventory of the glacial lakes in Nepal in 2001 which identified 3,252 glaciers with almost 3.6% (5,324 km^2) of the land area of Nepal. The inventory used a different information source, including the satellite images from 1999 and 2000, topographic map (1:63,360) published by India's survey department from 1957 to 1959 and aerial photography (Mool et al., 2001a). This inventory also mapped all glacial lake above 3,500 masl and total of 2,323 lakes with an area of 75 km^2 were identified. In 2011, ICIMOD published a new inventory of the glacial lakes based on the Landsat imagery.

2.3.2 The current scenario

There has been substantial glacial fluctuation during the 20th century on a global scale. Notably, towards the end of the 20th century, there has been dramatic glacier retreat in most of the world's alpine regions, with enhanced glacier and ice-field melts. The initial phase of this glacier retreat was linked with emergence from the Little Ice Age, which ended in the 19th century. It linked with warming of 0.30°C in the first half of the 20th century in the northern hemisphere. In the last few decades, a second 0.30°C warming has caused northern hemisphere temperatures to rise to unprecedented levels compared to the last 1,000 years (WWF Nepal Program, 2005). The 1990s were the warmest decade of the millennium and 1998 the hottest year of the millennium. In all, there was a temperature rise of close to 1°C across the continents.

As the global warming trend has continued, the last 40-year glacier over the mountain's region has decreased significantly. A recent comparative study of the historic glacier data and current satellite-based imagery from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) by USGS (United States' Geological Survey) shows that there has been a substantial shrinkage of mountain glaciers in the Himalayas, the Alps and Andes over the past decade (ICIMOD, 2010). Published results from other glacier studies around the world are consistent with this scenario. One of the IPCC's reports suggests that over 30 years between 1961 and 1990 the reduction in global glacier area amounted to between

6,000 to 8,000 km^2 among 200 mountain glaciers worldwide (Dyurgerov and Meier, 1997).

The measurements taken over the last century clearly show a general shrinkage of mountain glaciers globally (WGMS, 2001). The trend was most pronounced during the first half of the 20th century and glaciers had begun to grow again as of 1950. Nonetheless, after the 1980s the mountain glacier again started to shrink at a rate beyond the range of pre-industrial variability. IPCC (1995) and other scientific investigation (Oerlemans, 1994) concluded that by 2100 up to half of the global mountain glacier mass could be lost. Moreover, evidence shows that the Himalayan glaciers have been in a state of general retreat. These Himalayan glaciers are the lifeline for the most significant rivers in Asia: Indus, Ganga, Brahmaputra, Yangtze and Mekong throughout the years. Billions of people rely on these water resources, including India, China, Nepal, Bangladesh, and other countries in the region.

A popular climbing route to Mt Everest's summit, the Khumbu Glacier, has retreated more than five km since the 1960s. The average air temperature recorded at 49 stations of the Himalayan region since the mid-1970s rose by 1°C where an increasing warming trend towards the higher elevation sites was observed (Hasnain, 2000). The average warming for the mid-latitudinal northern hemisphere over the same period was 0.6°C (IPCC, 2001b), which shows that the mountain region is susceptible to climate change. By 2012, average surface air temperature across the Himalayan region has increased by 1.5ºC. A similar trend has occurred in the Arctic and Antarctic Peninsula (Shrestha, Gautam and Bawa, 2012).

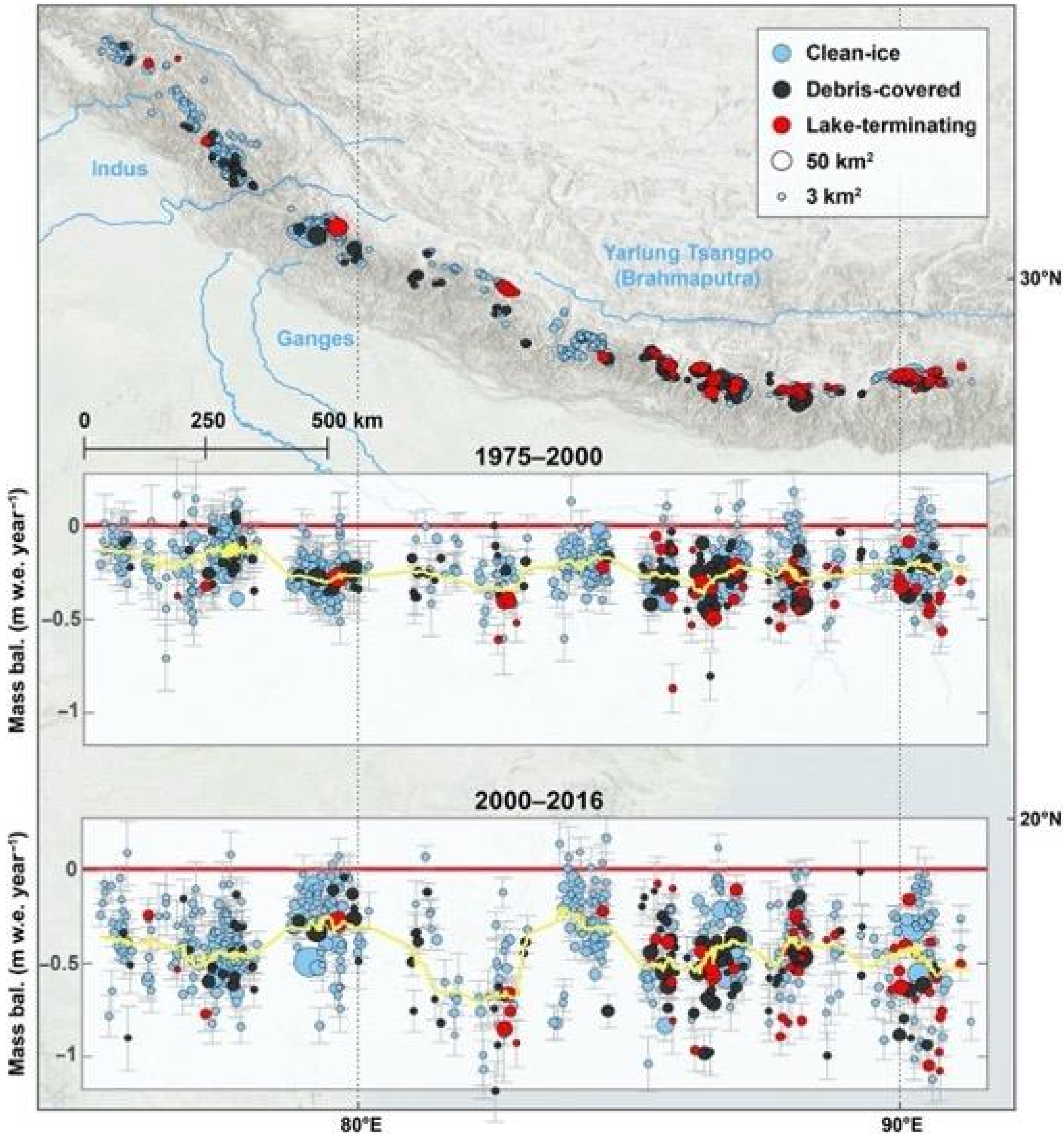

Figure 2.5 Map of glaciers and mass balance at HKH region. Glacier areas are proportional to circle size, colour shows clean-ice, debris-covered, and lake-terminating categories. Insets indicate ice loss during 1975 to 2000 and 2000 to 2016. (Maurer et al., 2019).

2.3.3 Overview of the problem

In the Himalayas, glacier thinning and retreat has resulted in the creation of new glacial lakes and the expansion of existing ones because of the accumulation of meltwater behind loosely formed natural moraine dams created as the glaciers attained their LIA Most of these lakes are highly unstable due to how they formed and subject to devastating drainage. Hence, they are a potential threat to the livelihoods down below the valley. Sudden lake discharges that produce a torrent of water and debris flow that may have catastrophic effects on its floodplain are called glacial lake outburst floods (GLOFs). As many glacial lakes are expanding at alarming rates in Nepal, their threat appears to be rising. In the recent past, there have been 24 GLOF events recorded in Nepal some of which have caused considerable damage to the people and property on its path. For instance, there have been the Bhote Koshi, Sun Koshi and Dig Tsho GLOFs of 1964, 1981 and 1985 respectively. The 1981 GLOF event damaged the road link to China and disturbed transportation for quite some time. The GLOF from Dig Tsho destroyed the Namche small hydroelectric project that was about to be completed. Some of these events originated from the Tibet Autonomous Region of China, showing the need for international collaboration and cooperation.

ICIMOD reported that the total glacier area reduced by 24% between 1977 and 2010, and the projected ice reserves by 29% (129 km^3), in the Himalaya region. As a result of fragmentation following shrinkage of the glacier number of glacier has increased by 11%. The lowest glacier area losses (gains in some situations) were witnessed from glaciers with a north or northwest aspect (of which there were very few) and slopes of less than 20°. Mountain basin type and valley glaciers also showed a lower proportional loss of area. Kulkarni and Pratibha (2018) used remote sensing data from the past 40 years, and a detailed analysis of 83 glaciers around the Himalayan region concluded a loss in glacier extent by 12.6±7.5% km. Furthermore, the maximum loss of glacier extent was reported in the Eastern Himalaya, near the Tista and Mt. Everest region, followed by Bhutan and Western Himalayas. This will significantly impact the biodiversity and lively of billions of the people across South Asia. Creating drought, flash flooding, glacial lake outburst flood, landslide and climate uncertainty. This will eventually diminish, forcing people to look for alternative livelihoods and creating climate refugees.

As apocalyptic as it might sound, it must be highlighted those glaciers need to be studied for different purposes including GLOF hazard assessment, adverse effects on hydrology, sea level rise and to monitor climatic variations. The glacier dynamics and other problems associated with retreating glaciers need to be understood to identify mitigating and implement glacial disaster risk reduction strategies. In this context, it would be imperative to understand the vulnerability of the glacial lake that is likely to cause GLOF, the region's central problem and also for high mountainous areas of the world. The comprehensive GLOF hazard assessment can be divided into a vulnerability assessment of the glacial lake and downstream impact assessment. The probability of catastrophic water release from a glacial lake is estimated through the lake, and natural dam breach hazard assessment, whilst the affected or likely to be affected areas can be identified during the downstream hazard assessment process.

There has been various research (Huggel et al., 2004; Richardson, 2010; Shrestha, 2010; Mergili and Schneider, 2011) conducted to perform the glacial hazard risk assessment. Most of these methods need some sort of field work. There is a lack of comprehensive methodology and framework to assess the Himalayan glacial lake's vulnerability based on remote sensing and satellite imagery datasets.

2.4 Observed and projected climate trend in Himalaya regions

Climate change is currently happening at an extraordinary level and this will put extra pressure on the environment and natural resources, which are associated with industrialization, urbanization, and economic development. Mainly, there will be widespread effects on the availability of, and access to, freshwater resources and a water-related hazard in the Himalayan region and surrounding. This section explores the observed and projected trend on climate including temperature, precipitation, river discharge and water-related hazard in the region.

2.4.1 Temperature

The analysis by the scientists at NASA’s Goddard Institute for Space Studies (GISS), concluded that since 1880 (when record-keeping began) the average global temperature on Earth has increased by more than 1°C Most of the warming trend has occurred since the year 1975 onwards, at a rate of approximately 0.15-0.20°C every ten years. In 2019, average global surface (land and ocean) was 0.95°C (1.71°F) more than 20th century average (Fig. 2.5) which was the second-highest temperature since 1880 and just 0.04°C less than the record value set in 2016 (NASA, 2020). There was a significant rise in the temperature in the past six decades throughout the HHK region (Rajbhandari et al., 2016). Ren et al., (2017) analysed century-long historical data sets that showed fluctuation in temperature trend at the HKH region. There was a moderate rise in temperature between 1901 to 1940s while the temperature was falling from 1940 to 1970, followed by rapid warming. During 1901-2014 spatial pattern of annual mean temperature on the HKH region increased by about 0.2°C per decade (Ren et al., 2017).

IPCC's fifth assessment report concludes that since the 1950s, there is more than a 90% chance that the observed warming is caused by greenhouse gas emissions from anthropogenic activities (IPCC, 213). It is projected that the temperature trend in the 21st century will be significantly higher than that was observed in the 20th century. The Asian continent will likely be warm, particularly the Himalayan region during this century; thus, a glacier in the Himalayan region will have adverse effects.

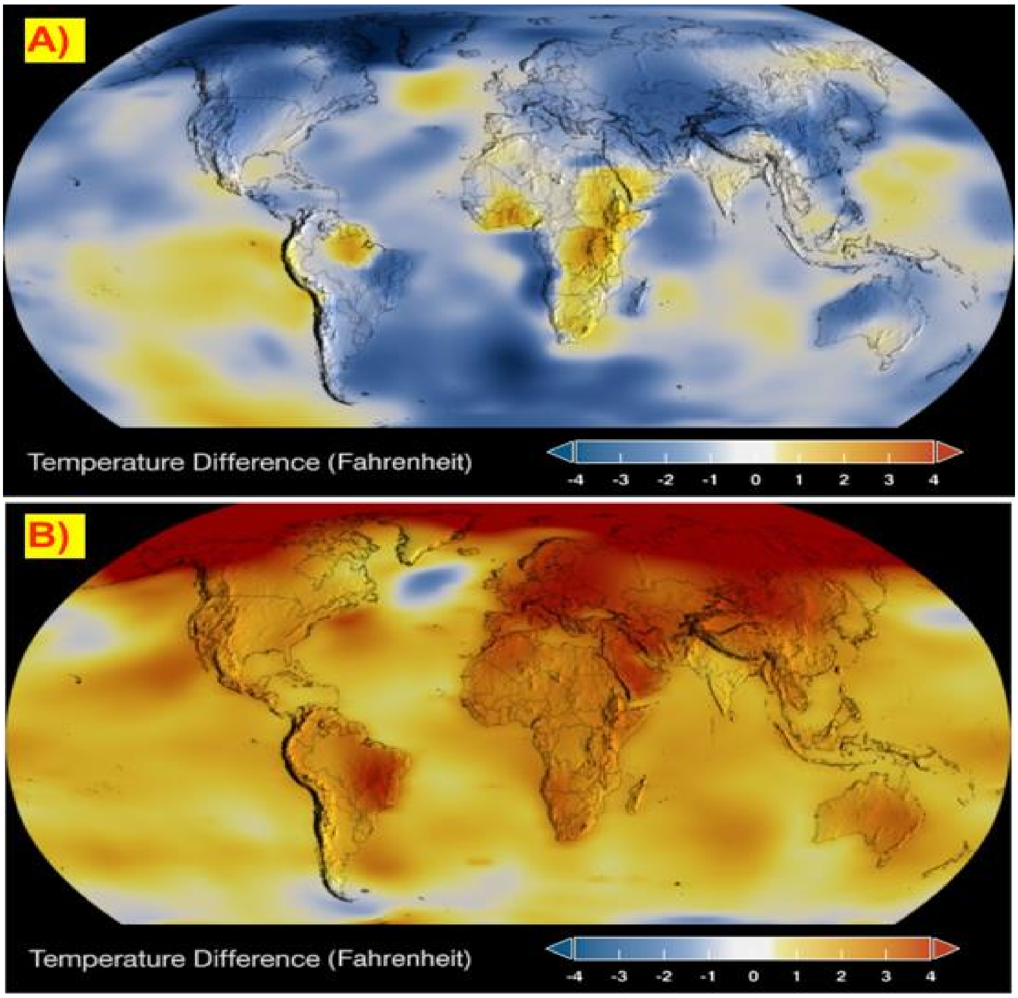

Figure 2.6 Earth's global surface temperature in A) 1899 and B) 2019. Since modern record-keeping began in 1880 the year 2019 was the second warmest (NASA, 2019)

It is predicted that the temperatures in the Indian sub-continent will rise between 3.5°C and 5.5°C by the 21st century. However, the climate models which are complex reactions to the greenhouse effect, may differ. Even high-resolution climatic models cannot give consistent projections of climate change in the Himalayas. Different studies suggest that warming in the Himalayas region has been much faster than the global average of 0.74°C over the last 100 years (IPCC, 2007; 2013). For instance, between 1977 and 2000, warming in Nepal was 0.6°C per decade (Shrestha et al., 1999). A similar trend was observed in Tibetan Plateau. It suggests that increasingly higher warming with higher altitude is a phenomenon predominant over the greater Himalayan region as a whole. Hence, the Himalayas and the Tibetan Plateau, as elevated regions of the world, are highly sensitive to climate change.

The recorded temperature data for Kathmandu (Nepal) was compared to the global data (mean over a span of 24° to 40° N latitude worldwide). It concluded a similar trend between these two series: the generally falling trend from the 1940s to the 1970s and the continuous rising trend afterwards. So, it is evident that Nepal's climatic variations are strongly connected to global changes in climate, perhaps being influenced by greenhouse gas emissions on the global scale.

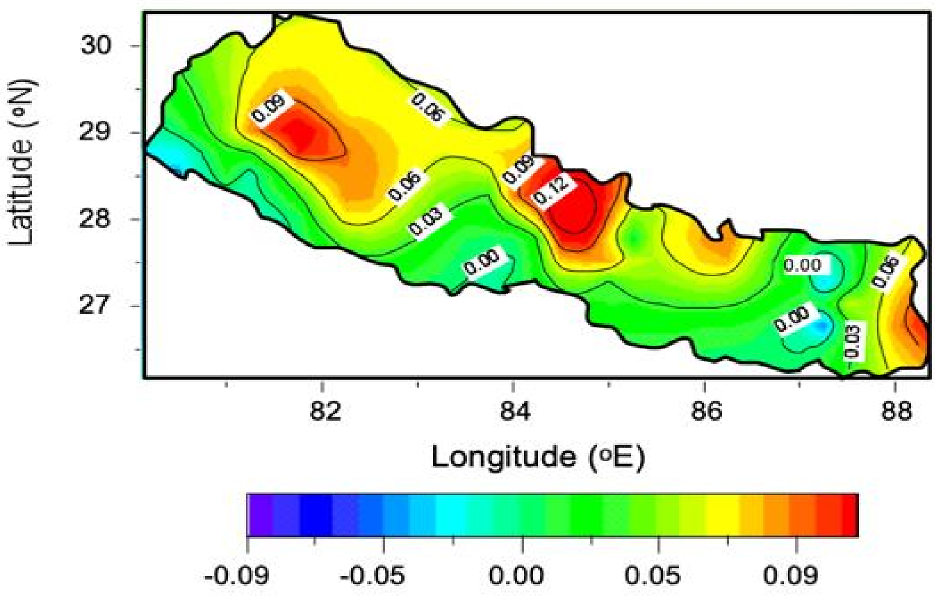

Figure 2.7 Spatial distribution of annual average maximum temperature trends in Nepal from 1977 to 1994, Colour Coding of temperature trends per year (UNDP, 2017)

2.4.2 Precipitation

In many HKH regions, a larger proportion of total precipitation appears to be falling as rain than resent past. Hence, snowmelt starts earlier, and winter is shorter; eventually, it will adversely impact the river flow regime, water supplies and livelihood. The conditions of the wetlands, glacial lakes, reservoirs, water flow and sediment transportation along the river also have an impact. Long-term paleo-climatic studies show that both dry and wet epoxides have occurred in the last millennium (Yao et al., 2008). However, the observational studies on the HKH region suggest that there is a rising trend in the number of wet days in recent past (Choi et al., 2009) on the Tibetan Plateau in the North-East region and Eastern and central parts whereas the western Tibetan region shows a decreasing trend (Xu et al., 2009). The precipitation records from Nepal between 1948 and 1994 show fluctuation between dry and wet periods, and there was no long-term trend (Krishnan et al., 2018).

The recorded dataset during 1951–2015 shows the spatial distribution of annual precipitation trends in the HKH region (Fig. 2.7). The substantial spatial heterogeneity in the region's annual mean precipitation is being observed (Fig. 2.8). As there is an increase in the precipitation trend over the Western Himalayas and the Eastern part of Himalayas, a weakening trend can be noticed over many areas in the HKH region. Northwest China, including the Tibet autonomous region and the high Himalayan area, witnessed wet trend over the decades.

The triangular markings in Fig. 2.8 indicate precipitation trends per decade based on a dataset for a more extended period of 1901–2013 (Chakraborty et al., 2020). The datasets show uniformity in precipitation enrichment over western Himalaya and weakening towards the north and central Indian plains. The annual precipitation reduction over India's northern part is also consistent with the recorded falling trend of the Indian summer monsoon precipitation throughout the post-1950 (Krishnan et al., 2015). In the monsoon, the precipitation is decreased by up to 20% by the end of the century in most parts of the HKH region. Due to the region's extreme, complex topography and lack of adequate rain-gauge data, most studies have excluded the Himalayan region, so extensive research is needed (Shrestha et al., 2000).

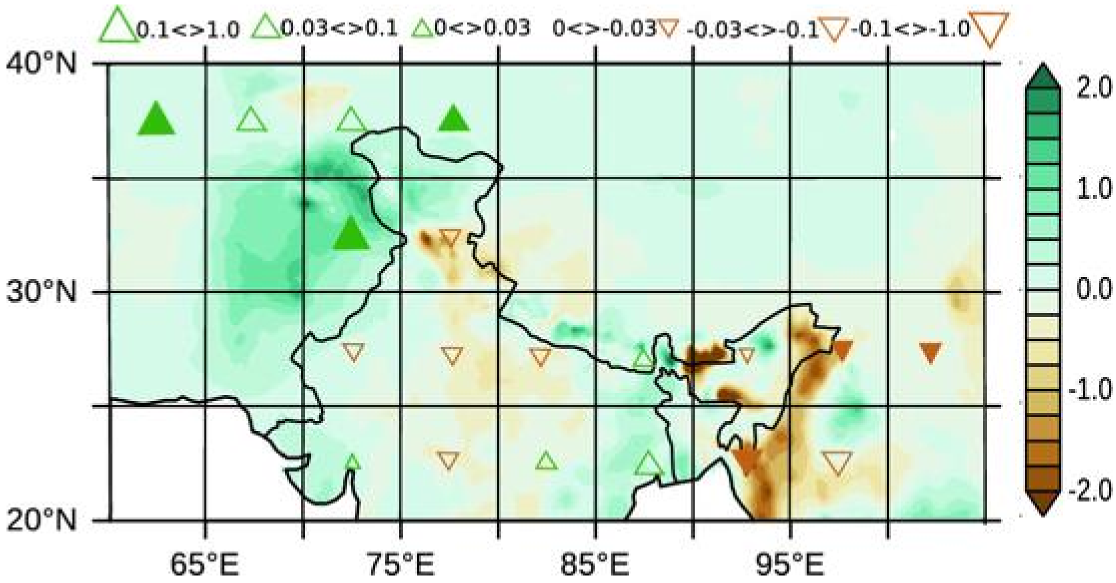

Figure 2.8 Spatial pattern of linear trends in annual mean precipitation anomalies (Chakraborty et al., 2020)

2.4.3 River Discharge

The rapidly changing climate has a tremendous effect to the people living on the lowlands that depend on the mountain water for their livelihoods including domestic, agricultural, and industrial needs (Graham et al., 2007). One-sixth of the world's population rely on mountain glacier and seasonal snow for its water supply which comprise more than 50% of the global river discharge. It is a complex process that concludes the conversion of precipitation into runoff and downstream flow, and there are several ways to do it. The total and peak river runoff primarily depend on precipitation type (rain, snow) and its amount, intensity, and distribution over time and space. The evapotranspiration (sum of all forms of evaporation plus transpiration) rates, related to temperature, also affect the water availability for runoff. The reduction of snow and ice, in the Himalayan region, which reduces the water storage capacity is the main consequence of the rapidly changing climate. Primarily, it is expected that the stable base flow derived from melting ice and snow will rise, mainly throughout warm and dry seasons. This will hinder the emergency initiative that needs to be taken by increasing the potential of the water-related hazard. As high-altitude reservoirs of ice and snow continue to decline, finally vanishing, the inconsistency of downstream river runoff will rise dramatically, and progressively reflect direct rainfall-runoff. As a result of this precipitation and evapotranspiration rates will increase.

The climate change induced glacial melt will seriously affect the people living in the HKH region the most. More than half a billion people living in China, Nepal, India, Pakistan, Bhutan and around the Himalayan region depend on the Himalayan glacier for their water supply from domestic use to agricultural and industrial use. They are also a source of the significant renewable energy sector (hydropower) of the region. Hundreds of millions of people in South Asia rely on perennial rivers such as the Ganges, Indus and Brahmaputra. They are all fed by the exceptional water reservoir formed by the more than 16,000 glaciers from the Himalaya. IPCC (2007a, 2013) suggests that the recent glacial retreat trends indicate that the low flow will become considerably reduced because of the rapidly changing climate. This will severely impact different sectors in the region including food production, availability of the freshwater, frequent extreme weather events that will eventually hinder the economic growth of the people living in the region and surrounding.

However, when the shortage arrives, it may happen abruptly, with water systems going from plenty to scarce in perhaps a few decades or less. It is projected that if the current global warming and glacier retreating trends continue for several more decades, one of the largest sources of the natural water reservoir will run out of water. The consequences may be more variable, and result in increasingly direct rainfall-runoff, thus leading to more flooding downstream.

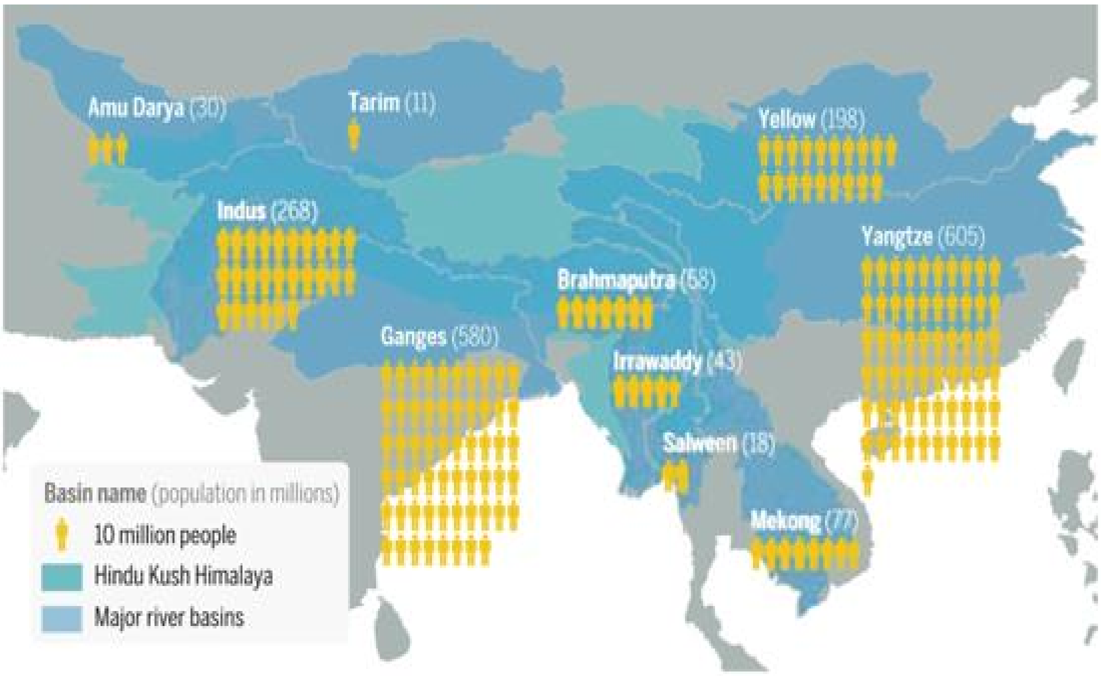

Figure 2.9 HKH region with population major river basin (Scott et al., 2019)

2.4.4 Water related hazard

Globally, Natural disaster takes 60,000 lives on average per year (Ritchie and Roser, 2020). The death rates are highly variable, ranging from 0.01% to 0.4%. In the last decade, the natural hazard was responsible for 0.1% of deaths globally. However, this is a large decline in comparison with the historical record. Historically, droughts were fatal disaster events, while the flood is the second highest reason after the present earthquake (Fig. 2.10). High death tolls tend to be focused in low-to-middle income countries by these natural hazards. People living in poverty are most likely to be affected due to the lack of infrastructure to protect and respond to these events.

Most people around the Himalayan region are living in poverty. According to the United Nations International Strategy for Disaster Reduction (UNISDR), in 2007, seven of the top ten natural disasters by the number of deaths happened in four countries (Bangladesh, China, India, and Pakistan) combined for 82% of total natural disaster-related deaths worldwide. This indicates that the region is very vulnerable to such disastrous events. The changing climate is often associated with extreme weather events, predominantly in combination with intensified monsoon circulations. The studies suggest an increase in extreme events, including high-intensity rainfall, often leading to flash floods and landslides (ICIMOD, 2007a; IPCC, 2013). In Himalayan region, increases in temperature will lead to an increased probability of such events that could adversely affect the livelihood and human settlements in the region and surrounding.

In the Himalayan region, rising temperature led to the formation of the glacial lake behind the terminal moraine and these high-altitude lakes are potentially dangerous. These glacial lakes can hold millions of cubic litres of water and potentially discharge with very high current and debris flow. These natural moraine dams are often vulnerable to extreme climate events as they consist of ice, loose sediment, and earth material. The breach of these moraine dams possibly leads to the catastrophic GLOFs, which can seriously damage life, property, farms land, and expensive mountain infrastructure. In the last 70 years, there have been twenty-five GLOFs events recorded within Nepal, whether it originated from Nepal or the Tibet, China (Mool, 2001a). Due to the rising temperature, the formation and expansion of new and existing glacial lakes are increasing, which further increases the frequency of GLOFs in the region. In the HKH region more than two hundred glacial lakes have been identified as potentially dangerous lakes, which can burst at any time (ICIMOD, 2008). While within the Nepal Himalaya there are about twenty-five PDGLs as of 2019.

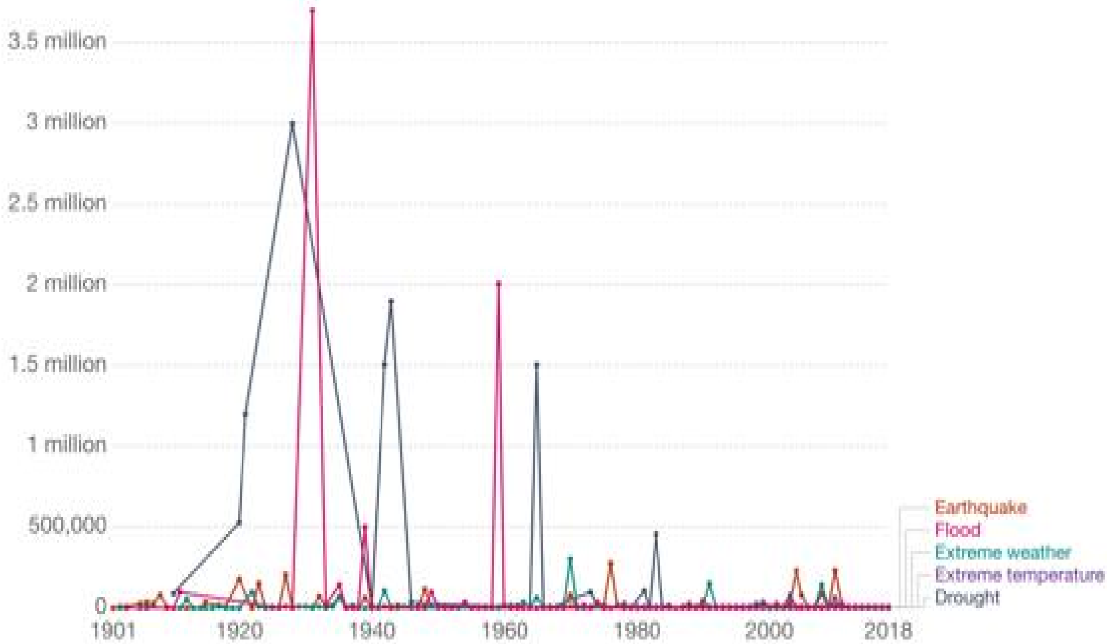

Figure 2.10 Global Death from Natural Disaster 1901 to 2018 (Ritchie and Roser, 2020)

2.4.5 Glacial retreat

Due to the changing climate and global temperature rise, most glaciers are shrinking or disappearing at an alarming pace. According to the World Glacier Monitoring Service between 1980 and 2018, glaciers worldwide (within 40 glaciers reference glaciers) have lost ice equivalent to 21.7 metres of liquid water. This is the equivalent of removing a 24-metre-thick slice from the top of these glaciers (Fig. 2.10). The IPCC (2013) predicts with high confidence that smaller glaciers in coming years may disappear entirely while others will be receding at a faster rate. Among the various research to model this ice retreating, one concludes that by 2050 35% of the existing glaciers will vanish (Shi, Liu and Kang, 2009).

The Himalayan glacier is receding faster than the global average. Glacial receding rate accelerated since about 1950s. Western China has lost 82% of its glacier (Liu et al., 2006) while the glacial area has increased by about 6.5% in Tibetan Plateau. Various factors accelerate glacial retreat in the Himalayan region, including heavy precipitation, temperature change, mass movement (avalanches, earthquakes, landslide, rockfall). The more extreme events happen the more glacier shrinkage will speed up. This will destabilize the glacial area, moraine dam, glacial lake, and surrounding, eventually leading to the catastrophic lake failure, GLOF. The excessive meltwaters, combined with heavy precipitation, may accelerate the flash flooding with devastating debris flow. There is growing evidence that the rapid mass movement has enormous influence in the HKH region's glacier retreat, particularly in the Himalayan region and in the Karakoram (Hewitt, 2005).

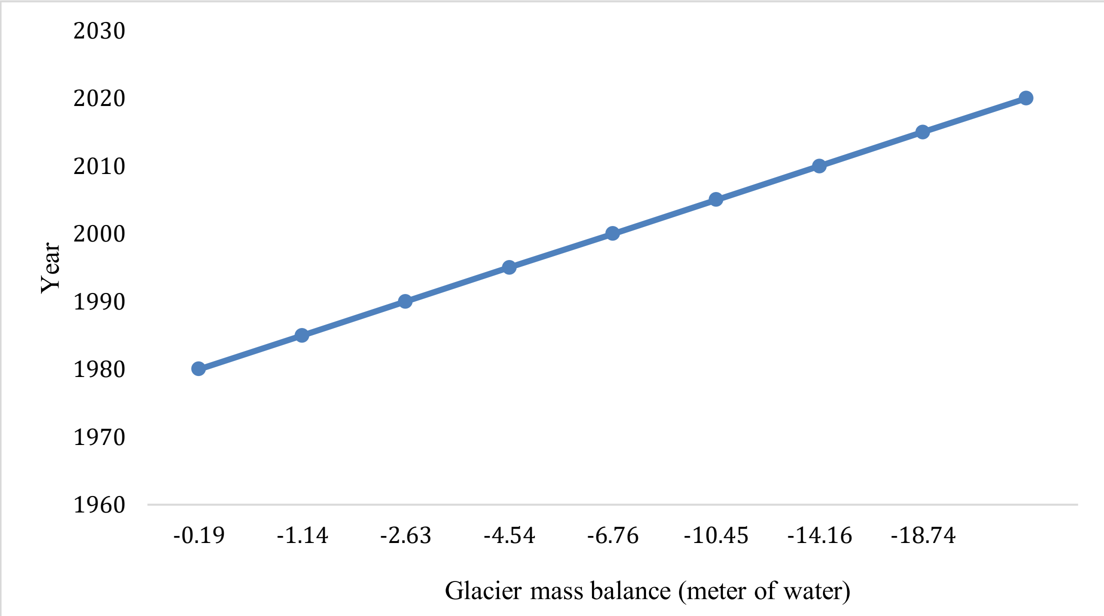

Figure 2.11 Global glacial mass balance worldwide (NOAA, 2020)

2.5 Impact of the climate change in the Himalayan region

Climate change has an enormous impact on the world's mountainous region, particularly in the high Himalayan region like Nepal. Shaped like almost a rectangle, Nepal lies between 80.4' and 88.12' east longitude and 26.22' and 30.27' north latitude. China is to the north and India lies in the other three cardinal directions (East, West and South). It is roughly parallel to the Himalayan axis about 800 km long and North-South width is about 140 km with an area of 147,181 km^2. It consists of snow and ice-covered Himalayas in the north to tropical forests in the South. The topography typically progresses from less than 100 m in the Southern Terai plain, up to more than 8,000m peaks in the north of the country. Hence, Nepal has a very varied environment and weather pattern. This section will explore the impact of changing climate to the county like Nepal.

2.5.1 Agricultural and farmland

To some 30 million people, Nepal is a developing country that relies on agriculture and remittance for its economy. In recent times, with staggering growth in population and food demand, even a slight fall in food production is a matter of concern. Extreme weather events, including heavy precipitation, landslide, glacial lake outburst flood, and flooding, are common in the region due to the loss of fertile top soil which further causes the decline in agriculture production in Nepal. Frequent changing climate may exaggerate this situation. There could be marginal yield rise in rice. That yield will continue to decline between 0.09 to 7.5% and beyond if there will be 20% in precipitation and 4°C rises in temperature (Krishnan et al., 2019). Nevertheless, the actual yield of wheat has increased in Nepal's western region with the increase in temperature while it has been falling in other regions. Hence, the increase in temperature has evoked mixed reactions in the region. Likewise, maize production has a negative impact due to the increase in temperature.

2.5.2 Biodiversity and wildlife

Nepal has an altitudinal variation of terrain ranging from 60 to 8850 m with diverse topography and distinct climatic regions (Bhattacharjee et al., 2017). Due to their harsh ecological and climatic condition, Nepal and the adjacent Himalayan region are predominantly vulnerable to climate change. Nearly a quarter of the land area is considered protected because Nepal is considered a hotspot for biodiversity. Frequent climate extremes are observed and predicted in the Himalayan region as tens of millions of people are dependent on the region's ecosystem services.

Rapid change in climate is becoming one of the significant environmental issues in Nepal. There is growing evidence that climate change is already affecting the biodiversity and reducing marginalised communities livelihood assets. Still, many people rely on forest products directly such as firewood, timber, medicine and food for their livelihood in Nepal. Its widespread exploitation and rising demand have led to a deterioration both in area and quality. This could have an adverse effect on the biodiversity as well as the very livelihoods of people. If this climate pattern continues, the cool temperate vegetation will turn to warm temperate vegetation and warm temperate rain forests and tropical wet forest may vanish (Regmi and Paudyal, 2009). Therefore, rapid climate change directly impacts the biodiversity, vegetation and wildlife of the region.

2.5.3 Human health and mountain infrastructure

Climate change and global warming hurt human health and mountain infrastructure. Mainly these effects can be divided into three categories including (i) direct impact due to heavy precipitation, drought, heatwave, GLOF and flash flood, (ii) indirect impact because of climate-induced socioeconomic conflicts, dislocation, crop failure, food scarcity, (iii) indirect impacts because of the spread of various infectious disease due to change in environmental circumstances (WHO, 2006). Similarly, valuable infrastructures such as roads, bridges, hydropower plants and communication systems, will be increasingly at risk from flooding and climate extremes.

Water-related diseases such as diarrhoea and vector-borne diseases such as malaria and dengue may expand rapidly due to climate extremes. These diseases are particularity vulnerable to the adverse effect of increasing temperatures (Sharma, 2012). Endemic morbidity and mortality because of diarrhoeal disease, linked with floods and droughts are projected to rise in East, South and South-East Asia as the hydrological cycle is predicted to change (IPCC, 2007a; 2013). Countries like India and China are at high risk of dengue fever, while mortality due to heat stress is also high.

Mountain infrastructure is at a vulnerable condition due to climate extremes and its consequences. The formation of pro-glacial lakes and the events of GLOFs is associated with glacier retreat due to changing climate. This GLOF and possible debris flow can have a devastating effect on essential and expensive mountain infrastructure downstream such as bridge, road and hydropower station (Yang et al., 2019). Mountain infrastructure often cost more than standard design due to its challenge to meet the geographic condition and technical details. If the current trend continues, it will be difficult to predict the river flow generation that will make hydroelectric power stations' operations more complicated (Thayyen, Gergan and Dobhal, 2005). This could have severe effects on water availability for power plants and other activities. Similarly, the dams and reservoirs are vulnerable due to the debris flow and sediment transportation.

2.5.4 Glacial Lake and Glacial Lake outburst Flood (GLOF)

These newly formed or existing glacial lakes are mostly unstable as they formed behind loosely tight end moraine dams. These glacial lakes are subjected to the catastrophic dam failure, potentially dangerous to the people living in the downstream floodplain. This sudden lake discharge and associated debris flow with a high current are known as a GLOF. In recent decades, the glacial lake is expanding rapidly, hence increasing the risk posed by them to the downstream community. Some of these events caused substantial destruction and loss of life in Nepal, for example, the Bhote Koshi GLOF of 1964, the Sun Koshi GLOF of 1981 and the Dig Tsho GLOF of 1985 (ICIMOD, 2011). The Dig Tsho GLOF had devastating damage on its floodplain including the destruction of the nearly completed Namche Small Hydroelectric Project. While the 1981 GLOF damaged only link road to China from Nepal for a few months.

These GLOF events happen on the international border. They can affect countries on both sides of the border. Hence international and regional collaborations are essential to solving these problems. However, glacial lakes pose potential sources of danger. They are also an essential natural asset that needs to be researched and developed more scientifically. They need to be mapped and monitored regularly to assess both their benefits and potential hazard. The regional authority and all stakeholders need to focus on preparedness, community resilience and climate change adaptation by reducing the risk. There have been various monitoring and disaster risk reduction activities going on around the world and in the region. However, there is a lack of comprehensive tools that are bespoke to the Himalayan region Nepal, based on available modern technologies, remote sensing and satellite imagery. The assessment that can be carried out remotely is critical, as most of these glaciated places are in difficult terrain and hard to get access to. They therefore demand more resources and expertise.

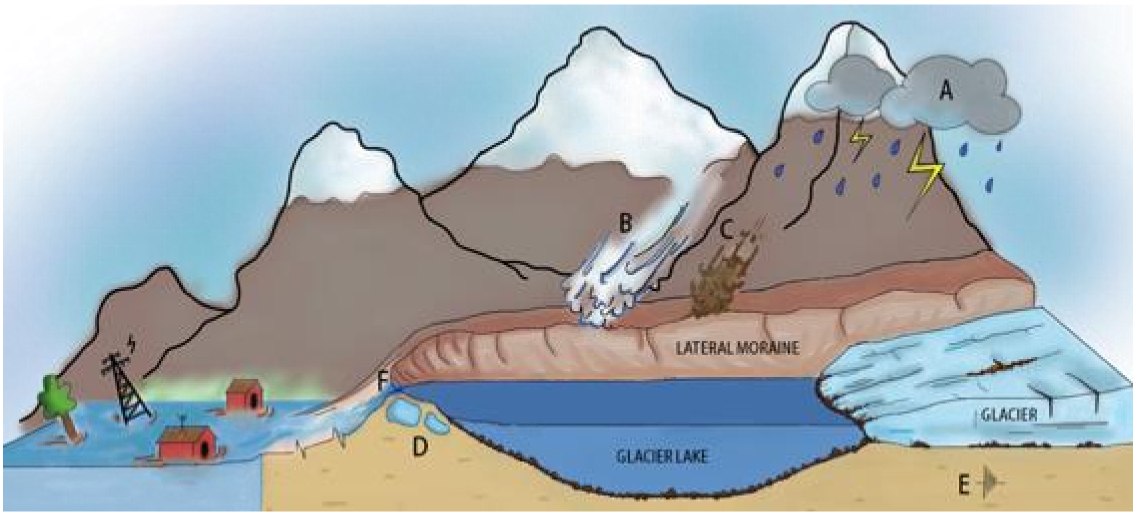

Figure 2.12 Illustrative drawing showing various GLOF triggering mechanism; (A) Torrential rainfall (B) Snow/rock avalanche (C) Landslide/rockfall (D) Melting of ice in moraine (E) Seismic movement (F) Dam overtopping (Modified from A. Kulkarni et al., 2018)

2.5.5 Mechanism of glacial lake formation in the Himalayan region

In the Himalayan region, glacier recession led to the formation of the moraine-dam glacial lake on debris-cover glacier tongues. At the beginning series of pond formed and then merged into enormous lake. It is crucial to identify these lakes as early as possible to plan remedial efforts as they are hazardous to the downstream communities and infrastructure. However, the correlation between glacial lake formation and glacier dynamic is not fully understood (Quincey et al., 2007).

The formation of the supraglacial lake is prevalent in the lake where the glacier surface gradient from the glacier terminus is less than 2° (Reynolds, 1999; Quincey et al., 2007). It is also evident that the glacial lake tends to develop at relatively thin debris layers of the debris-covered glacier (Suzuki et al., 2007). So, the glacier with a higher rate of ablation is likely to form a glacial lake in their terminus. It was also reported by Kirkbride (1993) that the supraglacial lake was formed when the glacier surface was lowered. The Imja lake (Nepal) formation and expansion observed by

Lamsal et al., (2011) between 1964 to 2006 led to a decline in glacier surface of approximately100 m.

Usually, in a debris-free glacier, the ablation reached a maximum at the glacier terminus. However, in a debris-covered glacier, the ablation rate is meagre at the glacier terminal but increases as it moves towards the equilibrium line from the terminus. The debris thickness increases from the equilibrium line in the debris-cover glacier, reaching more than one metre at the glacier's terminus. The ablation rate reaches a maximum in the middle of the ablation zone and decreases gradually as it moves towards equilibrium line due to the altitude and falling air temperature. Nuimura et al., (2011) found significant surface lowering in the middle of the Khumbu glacier ablation area in Nepal by studying the field observation data from 1978, 1995 and 2004.

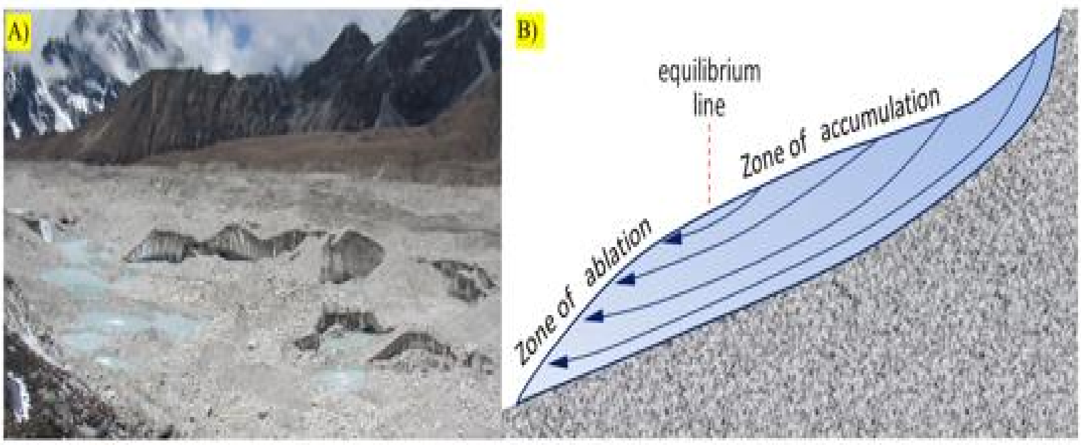

Figure 2.13 A) Khumbu glacier Nepal, B) Schematic diagram of glacier formation (Miles, 2021)

The formation mechanism of the glacial lake can also be identified by measuring topographic parameters of the glacial lake (Sakai and Fujita, 2010). The relative height between the glacier surface and later moraine ridges and inclination of the glacier surface. The topographic maps and data from field investigation, conclude that the value of the relative height difference between the glacier surface, exceeds 60 m in case of all large supraglacial lake in the region. The average surface inclination was concluded to be less than 2.0°. The glacier surface's low inclination shows relatively small ice flux to the lower part of the glacier that induces the glacier shrinkage (Fig. 2.14).

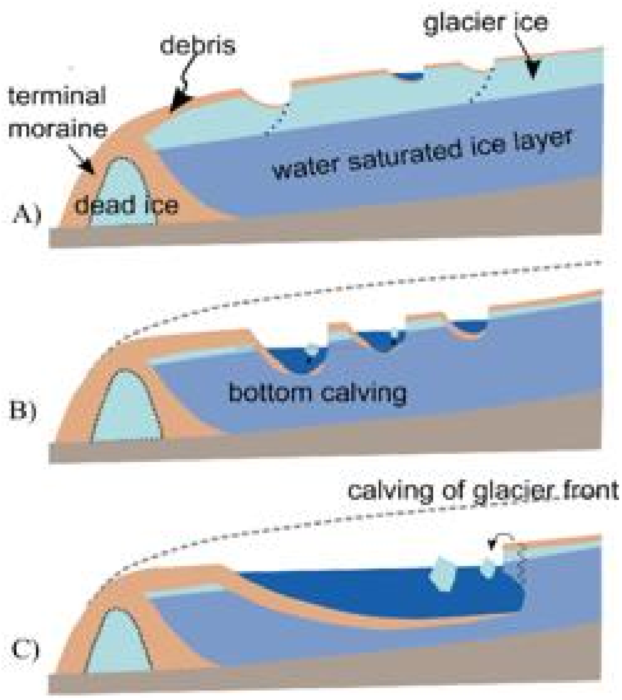

Figure 2.14 Schematic drawing of glacial lake formation mechanism, indicating the longitudinal cross section of the glacier terminus in debris cover glacier. A) Slow melting; thick debris layer and high glacier surface. B) Lake expansion by bottom caving. C) Rapid expansion of lake by calving of glacier front (Modified from Sakai and Fujita, 2010)

2.6 GLOF hazard mitigation and climate change adaptation

Since there is limited human control over natural events, it is vital to focus on mitigation measures, preparedness, and community resilience for natural hazards while reducing anthropogenic factors. There are many glacial lakes on Nepal Himalaya that pose enormous risk to the downstream community. They are a potential source of catastrophic GLOF, some of them have breached suddenly in recent past, causing colossal damage to the community downstream. The GLOFs and subsequent debris flows represent a significant threat in Nepal's high mountainous region and across the world. Changing climate has significantly influenced the region resulting in frequent extreme weather events leading to glacial hazard (Jones, Bartlettt and Learning, 2020). Hence, it is imperative to evaluate and quantify this potential risk to mitigate their catastrophic effects in this region. The GLOF hazard assessment can be completed in two phases: vulnerability of the glacial lake or probability of the water release and downstream impact assessment to assess the extent of the potential damage and other consequences. This research focuses on the former case to establish the vulnerability assessment framework of the Himalayan glacial lake, Nepal, based on remote sensing data.

A different approach has been developed to assess the glacial hazard around the world including empirical evidence (Huggel et al., 2004), geographic information systems (GIS) (Huggel et al., 2003, 2004b), remote sensing (Huggel et al., 2002; Allen et al., 2008; Fujita et al., 2008) and statistical modelling (McKillop and Clague, 2007b). Within these methods, remote sensing is considered the best way to examine glacial lakes and the impact of GLOFs in remote mountainous areas (Bolch et al., 2008). Because it allows greater flexibility in terms of data collection and accessibility of the site, particularly in retrospective investigations where GLOF events have occurred. However, these remote sensing techniques are usually developed to solve the particular region's problem such as in the British Columbia (McKillop and Clague 2007a; 2007b), in the Cordillera Blanca (Hegglin and Huggel, 2008) and in the Swiss Alps (Huggel et al., 2003).

To use these methodologies in the high Himalayan region such as Nepal, Himalaya warrants further studies. Moreover, the high-resolution data for the methods mentioned above may not be available from the remote Himalaya region Nepal, or maybe it is challenging to obtain due to extreme weather conditions, lack of ultra-modern technology and other various factors. Hence, to assess the expanding glacial hazard in the data's limited availability, the advanced approach is needed.

To reduce disaster risk, it is essential to understand the details of the hazard faced by the community. Good understanding of the hazard will enable all stakeholders, including engineers, planners, and scientists, to forecast the magnitude and frequency of the future events that will eventually lead to the better preparedness and community resilience. For instance, accurate GLOF forecast will allow the evacuation on the downstream floodplain in advance that will save many lives and property. Reducing exposure is critical to minimize or eliminate the adverse effect caused by the events. This can be achieved by community resilience, which often requires better planning, improving the community's awareness of persistent hazard, improving design specification and construction standard for mountain infrastructure. It requires all stakeholders including the international community, government and individuals to adapt to the changing climate.

2.6.1 Defining the Disaster Risks

Usually, a combination of the frequency and magnitude of the hazardous events is known as a risk that harms people's livelihoods. The United Nations Office for Disaster Risk Reduction (UNSDR) has defined disaster risk as 'the potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society or a community in a specific period, determined probabilistically as a function of hazard, exposure, vulnerability and capacity' (UNSDR, 2020). Thus, natural risks comprise of two components: the hazard, i.e., the probability of occurrence of the threat, and the degree of susceptibility of the element exposed to that source - vulnerability. The negative impact, or the disaster, will depend on the characteristics, probability and intensity of the hazard, and the susceptibility of the exposed elements.

$$\text{Risk} = \text{Hazard (H)} \times \text{Vulnerability (V)} / \text{Capacity (C)} \qquad (2.1)$$

Furthermore, natural phenomenon that could lead to damage, described in terms of its geometry, mechanical, and other characteristics' is defined as a threat. Hazard is the probability that a particular threat occurs within a given time and that involves the chronological distribution of the threat. Vulnerability is the set of conditions and processes resulting from physical, social, economic, and environmental factors. The threat can be existing or a potential which can define the magnitude of the catastrophic events. Generally, the geophysical condition can determine the magnitude of the events; in case of a GLOF the rate and volume of water that are likely to release and extend the damage it could cause downstream (Ives, Shrestha and Mool, 2010).

When it comes to natural hazard, the frequency of events is a critical factor, but it is challenging to estimate. Several events which occurred in the past and within particular circumstances will help to evaluate the probability of such an event recurring in the future. In the context of GLOFs, recurrence of discharge from the same source is minimal. Often as moraine-dammed glacial lake breach, the process occurs in such a way that the possibility of re-occurrence of the events is either eliminated or minimised mainly within the same circumstance.

2.6.2 Determining GLOF Hazard in the region

Since there is no definitive characteristic of the lake to suggest catastrophic drainage from the lake, it is necessary to establish the characteristics of the lake and subsequent GLOF events. The way they formed into glacial lakes can be divided into two categories; clean-ice glacial lake and supra-glacial lakes. On the steeply-slopped glacier, the lake formed between end moraine and its terminus with less debris is known as clean-ice glacier. While supra-glacial lakes are those that advance on the horizontal surface of the glacier tongue by the amalgamation of meltwater. Mostly, these types of the glacial lake form on the glacier surface that are entirely covered by the thick mantle of debris and have low gradients. As a result, their movement is prolonged, or they are entirely stationary, at least at their lower end where lake forms (Ives, Shrestha and Mool, 2010). As the supra-glacial lake advances and evolves, the ice underneath the glacial lake slowly melts, and they evolve as a moraine-dammed glacial lake.

Most of the existing potential dangerous glacial lakes in Nepal began as a supra-glacial pond and evolved through e.g., Imja Tsho, Tsho Rolpa, Thulagi glacial lake. Some of them are more than 2 km long and 100 metres deep with a storage capacity. The end moraine is a critical element to determine the stability of any glacial lakes in the region. Hence, once the integrity of the end moraine is compromised, the GLOF may trigger depending on the other factors which deteriorate the dam conditions. These are mainly the hydrostatic pressure due to the water volume and anything that makes it to rise. Any other factor that makes the moraine dam to compromise its stability should be considered. These can include any events related to the ice core melting any activities to reduce the outlet stream, and any resistance to the lake water’s natural seepage through the dam increasing the hydrostatic pressure as water volume increases. The mere possibility of the surge wave cannot be excluded depending on the area's topographic configuration.

The GLOF events can be triggered by either mechanism in both types of the lake, but the likeliness is different. In most cases, GLOF events from the clean-ice glaciers are triggered by the surge wave caused by the rapid mass movements (avalanches, landslides, rockfall) while the moraine dam collapse triggers supra-glacial lakes. Since the region is a highly active seismic zone, the distinction of these two sub-sets is irrelevant in the events of a significant earthquake.

Figure 2.15 Evolution of a supra-glacial lake and the formation of a moraine dam, Thulagi glacial lake (Dona Lake), Nepal (Gurung, 2009)

2.6.3 GLOF risk assessment and vulnerability of the glacial lake

Due to the complex nature of the triggering factor, GLOF events are complicated to predict. To conduct the lake and breach hazard assessment or to determine the vulnerability of the lake it usually includes two sets of parameters. The first considers the triggering factors while the second set of parameters examine the stability of the natural moraine-dam (Huggel, 2008; Mergili and Schneider, 2011). In extreme weather such as a major earthquake or any other unforeseen circumstance, this vulnerability assessment is less relevant.

Mainly in classic hydrology the flood probability and return period can be calculated from its frequency, but in case of the GLOF, it cannot be used because they are one-off events in most cases (Hegglin and Huggel, 2008). O'Connor et al., (2001), and Huggel et al., (2004) outline two GLOF hazard assessment processes. The first assesses the probability of water release (probable maximal flood volume and discharge) from the lake by identifying the potential hazard (i.e., lake and breach hazard assessment). Simultaneously, the second set of parameters examine the downstream hazard and assess the possibility of the debris flow and area that it may endanger. The severity of the impact downstream depends on the exposure. More exposure means more damage to people and infrastructure. The physical and social vulnerability of the can be determined by taking the risk assessment for infrastructure. There are various ways that this can be done. However, very little research work has been conducted to determine the glacial lake's vulnerability to determine the possible water release, particularly from the Himalayan region Nepal.

Methods to assess the possibility of water release from the glacial lake can be divided into three methods: qualitative, semi-quantitative and quantitative. These methods are categorised based on the stability parameter used to carry out the assessment, including the stability of the moraine-dam, adjacent glacier, geomorphology of glacial lake and surrounding. Different stability parameters used in past studies from different parts of the world are summarised in Table 1. Irrespective of the methods they follow some of the parameters are repeated. The distance between glacial lake and adjacent glacier (the primary source of water), the possibility of rapid mass movement (landslide, icefalls and rockfalls) due to dynamic slope failure are very important parameters. Since nature of the dam and its formation plays a vital role in the stability of the lake, its geometry including, the freeboard-to-moraine crest height ratio, the moraine width-to-height ratio, other internal characteristics of the dam and its structure (e.g., piping or the presence of an ice core) have been studied frequently.

The GLOF caused by the natural dam failure differs from place to place. So, it is vital to consider the regional specification to achieve more accurately defined hazard from the glacial lake. For instance, in North American Cordillera more than one-third of the GLOF events are triggered by intense rainfall (Clague and Evans, 2000) whereas in Cordillera Blanca Peru that is not the case. In Peru, most frequent GLOF triggering factors have been icefall, generating displacement wave while rockfall and landslide also triggered about 35% of the region's GLOF events (Emmer and Cochachin, 2013). Furthermore, since the Himalaya region is in the active seismic zone, earthquakes are another significant triggering factor that needs to monitor. Most of the past GLOF events in the Himalayan region Nepal and surrounding are caused by the trigger initiated by rapid mass movement (rock, icefall, landslide), avalanches, and internal structural changes of the natural dam leading to piping and ultimately dam failure.

Further investigation is needed to determine the assessment framework that suits the Himalayan region of Nepal and surrounding. The vulnerability parameters (stability characteristics) of the glacial lake must be relevant to the region's geomorphology and should be incorporated to assess the possible water release from moraine-dammed lakes in the Himalayan region Nepal and surrounding. Those vulnerability parameters of the glacial lake should be independent of each other and significantly contribute to the glacial lake's stability.

Table 2.1 Assessed stability characteristics from past studies

Stability characteristics	Previous studies											
	1	2	3	4	5	6	7	8	9	10	11	12
Armoured overflow channel (natural or technical)		✓		✓	✓							
Presence of buried ice in moraine dam		✓	✓			✓		✓	✓	✓	✓	
Compound risk present									✓			
Crevassed glacier snout above lake		✓			✓		✓					
Dam type			✓	✓			✓					
Debris-flow after GLOF* events										✓		
Distal flank steepness of the dam						✓	✓	✓				✓
Distance between lake and glacier	✓	✓					✓	✓	✓	✓		✓
Recent small GLOFs		✓										
Flash flood after GLOFs*										✓		
Area of glacier								✓				✓
Glacier advance		✓										
Glacier shrinkage										✓		
Glacier snout steepness		✓					✓	✓		✓		✓
Hydrometeorological conditions			✓					✓				
Area of lake								✓		✓	✓	
Changes in lake area										✓		
Lake depth							✓					
Dam freeboard	✓	✓		✓				✓				
Lake freeboard-to-moraine crest height ratio			✓	✓				✓	✓			
Lake volume							✓		✓			
Main rock type forming moraine											✓	
Moraine height-to-width ratio											✓	
Moraine slopes stabilised by vegetation						✓						
Moraine width-to-height ratio			✓	✓	✓		✓	✓				
Piping/seepage through moraine dam		✓		✓	✓		✓		✓			
Probability of landslide/rockfall into the lake		✓			✓		✓			✓		
Dynamic slope movements into the lake			✓			✓						
Possibility of snow/ice avalanche into the lake							✓		✓	✓		
Seismic activity in region							✓					
Slope between lake and glacier snout							✓					
Slopes of lateral moraine		✓										
Stagnant ice at the terminus										✓		
Supra/englacial drainage									✓			
Top width of dam							✓					

1. O'Connor et al. (2001) | 2. Grabs and Hanisch (1993) | 3. Huggel et al. (2004) | 4. Hegglin and Huggel (2008) | 5. Clauge and Evans (2000) | 6. Costa and Schuster (1988) | 7. Zapata (2000) | 8. Wang et al. (2008) | 9. Reynolds (2003) | 10. Bolch et al. (2011) | 11. McKillop and Clague (2007a, b) | 12. Wang et al. (2011) | * Downstream hazard assessment. | Source: Modified from Emmer and Vilímek, 2013.

2.6.4 Climate change adaptation

The term 'adaptation' started to become frequently used after the Intergovernmental Negotiating Committee, while drafting the United Nations Framework Convention on Climate Change (UNFCCC), formulated the term in 1992. It was one of the two types of response to climate change. Both in developed and developing countries worldwide, the concept of adaptation has been gaining momentum in recent years.

Adaptation is the key to achieving community resilience. People in the high Himalayan mountains are familiar with changing climate. Due to the geographical and other environmental factors in the high Himalayan mountains every aspect of life has been adapted to or stressed by extreme weather events, water availability, temperature regimes, avalanches, flash food and GLOF. These mountain people have a long history of adapting to these uncertainties and other environmental and ecological changes based on their local and traditional knowledge. Whether this is through living a flexible lifestyle or mobility of the people and land-use strategies, they have survived and lived in the region for millennia. Building on these more significant strengths of society to achieve community resilience is vital in achieving a more sustainable society and livelihood. This can be achieved by greater cooperation between different regional and global stakeholders with modern technology and empirical knowledge.

Rapidly changing climate and its consequences are more visible than before, and its consequences are becoming more devastating than before. Hence, climate change is evolving from the narrow hydro-meteorological sciences to the global issue that affects all aspect of human developments. So, there is growing consciousness among the international community on how to co-ordinate our response to changing climate because it is a trans-national issue than the regional or country-specific issues. For instance, few GLOF events originated in Tibet, China and cause devastating damage to Nepal and vice-versa. Therefore, adaptative policies to reduce the anthropogenic factors that accelerate the process have to be introduced as soon as possible, in all levels. The co-ordination from the different sector is necessary to achieve more sustainable and resilient livelihoods.

2.6.4.1 Flood forecasting and Disaster risk reduction

Floods, particularly flash floods are one of the major concerns in the Himalayan Mountain community where half of the world’s financially disadvantage people live. In many occasions’ mountain infrastructure has been destroyed due to the glacial lake outburst flood in the past. So accurate flood forecasting can save many lives and property by giving more time for preparedness. But unlike other flooding events GLOF is very difficult to forecast as it is one of flash flooding events in most cases. However, with help of modern technology the situation of the glacial lake and surrounding can be monitored and communicated to the local authority, community and people living in the downstream flood plain. Early warning system can be vital to save many lives and reduce the potential of such destructive events.

2.6.4.2 Community led adaptation

Climate change is a global issue that affects different parts of the world, but the poorer countries are the hardest hit due to lack of planning and inadequate infrastructure. Poor communities are vulnerable to various climate hazards, such as flooding, drought, landslides and temperature regime. They face water-related hazards in the Himalayan region, particularly GLOF. Considering the unavoidable local nature of the hazard, one must consider a series of activities which are truly rooted at the community level.

The community-led adaptation enables the local communities to understand the changing climate and consequences to daily life and required response to cope with instant climate variability and long-term climate change. The adaptation should be a 'bottom-up' approach based on local knowledge, needs, practices, priorities and capabilities. Hence, this should empower the local people and help to create more resilient communities. The priority should be on empowering the local communities to adapt to changing climate on their decision-making process and with the help of modern technologies and empirical knowledge from around the world. For instance, the Bangladeshi farmers build houses in stilts. Tibetan nomads have observed that spring is beginning earlier and they have moved yaks to alpine meadows earlier than previously practised. In Nepal people have installed community-based early warning system (partly successful) in Tsho Rolpa lake lowering project (Ives, Shrestha and Mool, 2010).

2.6.4.3 Public engagement and awareness

Increasingly the conversation regarding climate change is being recognised as key to solving many environmental problems and its consequence that the global society is facing today. Public participation is essential and necessary to give a platform to for everyone in society to speak. Furthermore, human values play a decisive role in shaping an individual's engagement with environmental issues (Corner, Markowitz and Pidgeon, 2014). Public engagement is vital, where local communities and indigenous people feel they are fully informed about climate change and its consequence in making an informed choice. They have the right to access the information in their way of communication or language.

The climate change policies on mitigation and adaptation will not succeed if they are not based on understanding the public attitude towards the climate risks and strategies taken to mitigate those risks (Corner et al., 2020). The climate changes adaptation strategies, and its technical environmental and economic consequences should be communicated to all stakeholders, including the general public and ingenious community. This will help to get a social mandate for the adaptation and disaster risk reduction strategies. Because generally, awareness and knowledge regarding climate change and its consequence in the region (e.g., GLOF, drought) among the general public and stakeholders are limited.

The regional and international policymakers need to consider the ecological, socio-economic and cultural implication of the climate change in the Himalayan region and communicate effectively with the general public and all stakeholders. As public engagement policies are supported by efforts to distribute information as much as possible, they also enable diverse voices to contribute to global and local discussions (United Nations Climate Change, 2021). This is very import to achieving a more resilient and sustainable society where climate extremes are very likely. The lack of integration with local community is the major problem and can be tackled through advancing the traditional knowledge and adopting a bottom-up approach in hazard mitigation.

2.7 Conclusions

The Himalayan region is extremely vulnerable to climate change and global warming (Bandyopadhyay and Gyawali, 1994). The Himalaya Mountain system is one of the complex mountains systems globally because of its altitude and various weather systems. It is complicated to understand the full extent of the damage caused by climate change in the region. However, increasingly ecological and socio-environmental change is occurring in the region affecting people's livelihoods. The glacial related issues, particularly the GLOF, are the real threat to the community, and it has caused devastating consequences in the past. So, it is vital that all stakeholders, including local authorities, planners, researchers and the global community, rethink how to respond to these changes and deal with possible upcoming changes. Dealing with climate change (i.e., GLOF) and its consequence are shared responsibility rather than that of the individual community or country. The adaptation and mitigation plan should be identified and be adopted as early as possible to avoid any catastrophic events. Various GLOF hazard mitigation plans have been researched in the past, but there is a lack of comprehensive GLOF vulnerability assessments framework based on the stability parameter and conditioning factor of the glacial lake in the Himalayan region.

For Himalayan people, changing climate and extreme weather conditions are common phenomena, but the frequency of the extreme events in recent decades is a worrying sign. In this region, every aspect of life has been stressed by the changing climate and its consequences for a very long time. They have a long history of adapting and changing their way of life, through the mobility of the people and land use to living a flexible lifestyle. People in the Himalayan region have lived with and survived many significant hazards. Nevertheless, building on this capacity and strengthening their socio-economic conditions is a necessary and crucial step towards achieving a more sustainable and resilient community.

The main challenge in the part of the world is the uncertainty of the primary dataset. Due to the remoteness of the extreme event's location, there are very few catastrophic events recorded and analysed in the past. This is even more relevant in the context of frequent extreme events. The dynamic of the Himalayan climate and its hydrological process is complicated. Hence, their response to changing climate is also uncertain.

The long-term monitoring, networking, open data exchange, and cooperation between all Himalayan countries need to work together to reduce the looming threat (Shrestha, 2000). User-friendly adaptive policies should be implemented to reduce and reverse anthropogenic drivers of climate change in the region, particularly glacial related hazard (i.e., GLOF). There is a lack of comprehensive risk assessment tools to measure the glacial lake's vulnerability or its stability in the region. The present study proposed inclusive vulnerability assessment tools based on the stability parameters (geomorphological and geometrical) and conditioning factor of the glacial lake, host glacier, and surrounding. The proposed assessment tool is primarily based on remote sensing data and empirical evidence. Hence, it can be carried out remotely to assess the rural geographical location, which will save time and money. It would help both local communities and decision-makers understand the glacial lake's current situations, thereby facilitating them to assess their adaptability to the forthcoming change by appropriate planning and design.

Chapter 3

Characteristic of historic GLOF and downstream impact assessments

This chapter explored the hydrodynamic characteristic of the GLOF and its impacts at downstream floodplain and their long-term consequences. The 1998's GLOF event at Tam Pokhari, Mt. Everest region Nepal was modelled and analysed in terms of its downstream impact using HCE-RAS 5.0.7. Also, it examined the socio-economic impact of the past GLOF events in the study area. The erosion and sedimentation in downstream floodplain (U-shaped, V-shaped valley) is explored.

The GLOF is a type of the flash flood that has high velocity with great depth and possible debris flow. This can have devastating effects on the entire mountain community and riverine landscape. Due to the ongoing change in climate and global warming, the formation of the new glacial lake is more rapid in last 3 decades, hence increasing the possibility of the GLOF. It is very crucial to investigate the past GLOF events to understand their characteristics. This will help to reduce their negative consequences and identify the hazard mitigation measure in the region and same geographical settings around the world.

3.1 Introduction

It is evident that global warming as consequence of the climate change is resulting in extreme natural events (e.g.., flash flooding) being more frequent than recent past GLOF is one of those extreme events that has long-term adverse effects on people's livelihood. However due to the lack of data, the most remote locations of the GLOF process chain have not been investigated thoroughly. There are very few scientific papers published on the actual account of the events. Most of the available reports and papers are mostly based on historical accounts of the previous events and remote sensing monitoring and early warning system and their instillations. There is very few scientific research works focused on the hydro-dynamic characteristic of the glacial lake outburst flood flow events. Despite the lack of accurate information most of the historic GLOF events are considered as debris flow. In this research the 1998's GLOF event at Tam Pokhari, Mt. Everest region Nepal was investigated and the downstream impact was analysed. The HEC-RAS 5.0.7 was used to perform hydro-dynamic modelling.

Often, the post-GLOF impact (erosion and sedimentation) is considered as secondary hazard which will have persistent damage to the socio-economic structure of the community. The discharge and velocity of the GLOF are extremely high which makes it impossible to measure it during the events. Hence, it is very important to conduct the investigation after the GLOF events. It is evident that there is higher sediment concentration in the river after the GLOF events. Generally, total sediment is accepted as wash load that moves through a river system and eventually deposited in river deltas (Reynolds, 1999).

The impact of the GLOF and characteristics of the flood flow are dominated by the geological and geographical structure of the region. The formation and types of geomorphologies can determine the rate of erosion during the GLOF process. The instance velocity of the GLOF may induce instability in these riverbed slopes due to lateral erosion. In the Himalayan region, narrow V-shaped valleys are mostly created by river incision at lower segments of the U-shaped valley. It is necessary to understand the behaviour of the GLOF in the region as the frequency of the GLOF continues to increase and threaten planned and existing infrastructure project (Nie et al., 2021). So, it is vital to investigate their characteristics and possible downstream impacts in detail.

3.2 Hydrodynamic characteristic of GLOF

The GLOF process chain can be evaluated by two methods: water only flow and water-sediment mixed flow. The kinematic wave models can be used to evaluate the event in the former case. With the latter case, governing equations for the flow of a mixture can be employed to examine the GLOF flow process. Employed equations should be applicable for sediment-laden flow however, ranging from usual bed load to debris flow (Osti and Egashira, 2009).

There are several different equations proposed by various researchers to evaluate the water-sediment mix flow, but Egashira, 2007 classified them mainly in four categories.

1. Coulomb-type shear stress (Savage and Hutter, 1989, Iverson and Denlinger, 2001)
2. Bingham-type (Chen, 1988; Julien and Lan, 1991)
3. Fluid-type (Takahashi, 1980)
4. Coulomb-type shear plus fluid type (Egashira and Ashida, 1992)

Each group has their own merit and demerits. For example, steady-state solution, an important element of the flow can only be described by type 4 questions, while type 1 cannot describe it. Moreover, the type 2 equations (Bingham) do not differentiate between the flow over a rigid bed or an erodible bed appropriately. Likewise, type 3 equation (Fluid-type) cannot describe how the flow body stops, while types 1 and 4 can. Egashira et al. (1997) proposed the formula to describe the flow of a mixture of water and coarse sediment over erodible and rigid beds while assuming that the turbulent suspension is negligible. These formulae can be used to evaluate profiles of velocity and sediment concentration as the flow changes from a bed load layer to debris flow in response to a monotonic change in the flux sediment concentration. (Egashira et al., 2001a). These formulae can also be used to reproduce inverse profile of the sediment concentrations that can be formed over a rigid body.

Since, GLOF flow mechanisms is largely known it is hard to determine the true extent to the damage that can be caused by GLOF at different geomorphological settings. Hence it is urgent to evaluate the GLOF flow process chain as well as establish reliable and scientific methodologies for prevention and mitigation of GLOF disaster at different settings. So, this study has utilized the debris flow model proposed by Egashira et al., (1997), to advance a reliable method for evaluation of the flood flow process associated with GLOFs. Tam Pokhari GLOF that occurred at 1998 in the Mt. Everest region is been investigated to establish the flow characteristic and sediment behaviour in the GLOF process chain by hydrodynamic flow modelling. This will help to mitigate GLOF hazard assessment in the region and similar geomorphological setting that will contribute to build community resilience and sustainable development.

3.2.1 Glacial Lake outburst flood flow mechanism

Most of the glacial lake outburst floods are associated with debris flow or debris-laden flash flood. Mainly the debris flows are water-saturated mass of fine sediment, rocks, and assorted debris that originate on mountain slopes and downstream channels when they reach valley floors and floodplains (Iverson and Denlinger, 2001). In debris flows, the strong interaction between fluid forces and solid significantly influence the behaviour of the flows. This differentiates them from other related mass movement and related phenomena such as avalanches, water floods and landslides. Nevertheless, flash floods can resemble debris flows if floods contain sufficient debris or coarse sediment to significantly raise the friction at the fronts of advancing bores.

Iverson and Denlinger (2001) considered that the debris flow acts as mixture of interacting Coulomb solids and Newtonian fluids. Parts of the solid and fluid obey three-dimensional mass and momentum balances, that are summed and depth integrated to generate the equation that describe shallow flows of the mixture as a whole. These mixture equations and standard shallow-water equations distinguish each other due to the strong variation of flow resistance and to interacting solid and fluid forces. The fluid pressure is the key component which evolves as the flow progresses, thus segregating of flow resistance between solid and fluid components depends on it. The equations reduce to the conventional shallow-water form, if fluid pressure supports the total weight of the flowing mass, all resistance results from hydrodynamic forces. If fluid pressure supports none of the weight of the flowing mass, all flow resistance is due to Coulomb friction between interacting solids, and the equations describe motion of granular avalanches (Iverson and Denlinger, 2001). A mixture of solid and fluid resistance typifies debris-laden flash floods and debris flows.

3.2.2 Debris flow modelling

The glacial lake outburst flood flow with sediment transportation due to the 1998 GLOF at Mt. Everest region, Nepal has been simulated using the 1D governing equations proposed by Egashira et al., 2001b. The governing equations were solved by the constitutive equations and erosion rate formula suggested by Egashira et al. (1997, 2001b).

The water-sediment mixture and sediment only flow can be expressed as mass conservation equations:

$$\frac{\partial h}{\partial t} + \frac{1}{B}\frac{\partial \bar{u}hB}{\partial x} = \frac{E}{c*} \tag{3.1}$$

$$\frac{\partial \bar{c}\,h}{\partial t} + \frac{1}{B}\frac{\partial\, \Upsilon\, \overline{cu}\, hB}{\partial x} = E \tag{3.2}$$

The momentum conservation (3.3) and bed elevation (3.4) equations are as below:

$$\frac{\partial hu}{\partial t} + \frac{\partial \beta h\overline{uu}}{\partial x} = gh\sin\theta - gh\cos\theta\frac{\partial h}{\partial x} - \frac{\tau_b}{\bar{\rho}_m} \tag{3.3}$$

$$\frac{\partial z_b}{\partial t} = -\frac{E}{C*\cos\theta} \tag{3.4}$$

Here, the flow depth is h, the time is t, the coordinate towards the flow direction is x, the erosion rate of the bed sediment (its negative value denotes deposition) is E, the depth-averaged and volumetric sediment concentration is $\bar{c}$, the sediment concentration of the underlying sediment bed is c_* , the depth-averaged velocity of the mixture is $\bar{u}$, river bed width is 'B', the acceleration due to gravity is g and the depth-averaged mass density of the sediment–water mixture is $\bar{\rho}_m$, that can be expressed as:

$$\bar{\rho}_m = (\sigma - \rho)\,\bar{c} \tag{3.5}$$

Where, σ, ρ, τ_b, z_b, is the mass density of the sediment particle, mass density of water including fine sediment, bed shear stress, bed elevation from a reference level respectively and the θ is the bed slope, which can be expressed as:

$$\theta = sin^{-1}\left[-\frac{\partial z_b}{\partial x}\right] \tag{3.6}$$

$\gamma = (1/A) \int_A \{(c\, u)/(\bar{c}\ \ \bar{u})\}$ dA in equation (3.2) is a shape factor with a value that ranges from 0 to 1, depending on the bed slope and inter-particle friction angle. In equations (3.3), β is the momentum-correction factor, where $\beta = 1.10$ to 1.40 for debris flow (Egashira et al., 2002).

The equations for the bed shear stress and erosion rate are also expressed as:

$$\tau_b = \tau_y + \rho\, f\, \bar{u}^2 \tag{3.7}$$

$$\frac{E}{\bar{u}} = c * tan(\theta - \theta_e) \tag{3.8}$$

Here τ_y is the yield stress due to particle-to-particle contacts, θ is the bed slope, f is the friction factor and θ_e is the equilibrium bed slope corresponding to the sediment concentration $\bar{c}$ of a debris flow. Other factors τ_y, tan θ_e and f can be stated as:

$$\tau_y = \left(\frac{\bar{c}}{c*}\right)^{1/5} (\sigma - \rho)\, \bar{c}\, g\, h\ cos\,\theta\ tan\,\emptyset_s \tag{3.9}$$

$$tan\,\theta_e = \frac{\left({}^{\sigma}/_{\rho} - 1\right)\bar{c}}{\left({}^{\sigma}/_{\rho} - 1\right)\bar{c} + 1}\ tan\,\emptyset_s \tag{3.10}$$

$$f = \frac{25}{4}\left[k_f\, \frac{(1-\bar{c})^{5/3}}{\bar{c}^{2/3}} + k_d\left(\frac{\sigma}{\rho}\right)(1 - e^2)\bar{c}^{1/3}\right]\left(\frac{h}{d}\right)^{-2} \tag{3.11}$$

Here d is the particle diameter $k_f = 0.16$, $k_d = 0.0828$ and e and $\emptyset_s$ are their restitution coefficient ($e = 0.85$) and the inter-particle friction angle of sediment particles, respectively. Evaluation of satellite imagery, published report, field survey report, and expert knowledge in field have been used to extract the physical parameters such as flow width, physical properties of the sediments and potential erosion depths. The bed material properties were as follows:

Particle size diameter $(d) = 20\ cm$.
Mass density of sediment $(\sigma) = 2.65\ g/cm^3$.
The average river bed width $(B) = 50 - 80m$ range.
Inter-particle friction angle of the sediment particles $(\emptyset_s) = 34^{\circ}$.
Mass density of interstitial fluid with suspended sediment $(\rho) = 1.33\ g/cm^3$.
The sediment concentration of the underlying sediment bed $(c*) = 0.52$.
The potential erosion depth (depth of unstable sediment overlaying the bedrock) $(d_p) = 9m$.

The finite leapfrog difference scheme was used for computations with time $t = 0.012\ s$ and $\Delta\ x = 20\ m$.

In this study, flux sediment concentrations of debris flow reflected were lower than those of usually accepted as debris flows. Nevertheless, the word 'debris flow' is used to make it less complex because the dynamic characteristics of the debris flow change monotonically with sediment concentration (Egashira et al., 1997). If sediment particles composed of the flow body are so coarse that turbulent suspension is impossible, the sediment concentration in debris flow can be determined uniquely in an erodible bed.

3.2.3 Hydrodynamic (water-only) modelling

There are various software and techniques that have been used to model the hydro-dynamic characteristics of the flood at different circumstances. But a good hydraulic model requires good geometry and flow data. The effectiveness of the simulation depends on the type of model i.e., one dimensional (1D), two dimensional (2D) or combined approaches. Historically 1D models have been used extensively to model the flow in the main river channel and in certain cases it has been very effective in predicting flood extent (Vozinaki et al., 2016). 1D modelling has computational efficiency and parameterization in dealing with flows in large and complex networks even though it cannot simulate two dimensional flow path in large floodplain. 1D model has limited application but is economical, robust, provides valuable information on water profile properties and is a popularly preferred alternative, as long as the flow paths can be identified.

The 2D modelling approach describes a good floodplain flow performance but requires significant amount of data and is not suitable for short timescale and lack of floodplain geometry data condition. Nevertheless, with the development of remote sensing technology today, high-resolution topographic data can be generated to represent accurate floodplain geometry data derived from satellite imagery. Although, the presence of this high-resolution data is still unavailable in different part of the world particularly developing countries. Integrating 1D/2D model in urban flood modelling was found to be efficient but the application depends largely on high-resolution data availability (Vozinaki et al., 2016).

There has been various research conducted by performing 1D modelling in the hydraulic simulation which concluded that 1D model is capable of giving a good estimation of flood level and duration and can be used for prediction of flood extent (Horritt and Bates, 2002). The researchers used geometry data from a combination of surveyed and digital elevation model (DEM) to predict the flood level and other variables successfully, because importance of accurate geometry data in 1D hydrodynamic model is vital. These studies confirm the cost-effective, reduced complexity and reliable prediction of water level along the river of the 1D model. In this research, 1D modelling approach was implemented as a primary study to certify the base model and ability of HEC-RAS 5.0.7 in simulating extreme event of the large-scale river before advancing towards combined 1D/2D modelling as further complex modelling.

3.2.3.1 Overview of HEC-RAS Modelling

HEC-RAS is a well-established and well-tested hydraulic model designed by the US Corporation Engineers Hydraulic Engineering Centre to model river flow (Brunner, 2016). It has been used extensively in river modelling and flood hydraulic simulations. It allows users to estimate water surface profile along a river in a steady and unsteady flow and also river hydraulic calculation including sediment transport modelling. Its basic computational procedure is based on the solution of one-dimensional energy equations. Energy losses are evaluated by friction (Manning's equation) and contraction\expansion (coefficient multiplied by the change in velocity head). The momentum equation is utilized in situations where the water surface profile is rapidly varied. These situations include mixed flow regime calculation, hydraulic of bridges, and evaluating profiles at river confluences (Brunner, 2016).

Energy and momentum equations (3.12 and 3.13) are used to derive 1D Saint Venant equation in solving steady and unsteady state flow water surface profile simulation within HEC-RAS using implicit finite different method.

$$\frac{\delta A}{\delta t} + \frac{\delta S}{\delta t} + \frac{\delta Q}{\delta x} - q = 0 \qquad (3.12)$$

$$\frac{\delta q}{\delta t} + \frac{\delta (VQ)}{\delta x} + gA\left(\frac{\delta z}{\delta x} + S_f\right) = 0 \qquad (3.13)$$

Here, A is the cross-section of the area, t is the time, S is the ineffective flow area, Q is the discharge, q is the inflow per unit area, x is the distance along the channel, V is the velocity, z is the elevation, S_f is the friction slope and g is the gravitational acceleration. The unsteady flow simulation component in HEC-RAS modelling system is capable of simulating 1D unsteady flow through a full network of open channels. In this study, HEC-RAS version 5.0.7 is used to model GLOF event from Tam Pokhari lake that occurred in 1998.

3.3 HEC-RAS Modelling of Tam Pokhari GLOF, 1998, Nepal

3.3.1 The study sites

Tam Pokhari (Sabi Tsho) is situated at 27° 44′ 34″ N, 86° 50′ 41″ E at the Mt. Everest region in the Dudh Koshi basin, Nepal. This is one of the most glaciated basins within the Nepal Himalaya, where a record number of glaciers have been retreating and contributing to increasing number of glacier and its proliferation (Bajracharya et al., 2009). As this region gets precipitation mostly in summer months (June to September) glacier nourishment mainly relies on summer precipitation, and both the maximum accumulation and ablation of glaciers instantaneously happen during these periods.

Figure 3.1 Ongoing dam breaching at Tam Pokhari (Sherpa, 2018)

On 3 September 1998 Tam Pokhari Glacial Lake suffered outburst and caused the damage on downstream floodplain. The flood swept away several bridges, damaged agricultural lands and dammed the Dudh Koshi River for 2 km upstream (Dwivedi et al., 2000). In the main, destruction is caused by the sediment transported by the flood (Osti and Egashira, 2009). Dwivedi et al., (2000) and an eyewitness, Lakpa Gyaljeng Sherpa, claim that the outburst was triggered by an ice avalanche while there is strong evidence presented by Osti et al., (2011) that the landslides from lateral moraine into the lake triggered the GLOF.

According to the eyewitness, numerous overtopping surge waves occurred before they incised the moraine dam completely. Figure 3.1 shows the progressive outburst, glacial lake, surrounding and Fig. 3.2 reveals the Taknak village as they survive the outburst.

Figure 3.2 Taknak village in 2009 after GLOF events at 1998 (Lamsal et al., 2015)

3.3.2 Data and method

In this research HEC-RAS 5.0.7 was used to perform 1D unsteady-flow calculations providing dam-breach hydrographs as the upstream boundary condition and the energy slope as the downstream boundary, which was assumed to be nearly equal to the river bed slope. It solves the Saint Venant equations formulated for natural channels using the well- known four-point implicit box finite difference scheme (U.S. Corps of Engineers, 2016). The Inkhu river, approximately 11km downstream from the lake has been modelled based on their drainage features (Fig. 3.4). It is very difficult to conduct the one-dimensional (1D) hydro-dynamic flood-routine using HEC-RAS 5.0.7, particularly in narrow, steep and gravel-bed rivers like the Inkhu. Nevertheless, several researchers including Hicks and Peacock (2005) have concluded that the results produced by HEC-RAS 5.0.7 in similar contexts have been found to be reasonable when compared to the results from many other 1D hydrodynamic models.

Data Collection and management

- Creating preparing data from various platform (QGIS, Google Earth)
- Creating Digital Elevation Modeling (DEM)
- Terrain Development
- Identifying river cross-section

⇩

Data Input

- Boundary conditions (Upstream; flow hydrograph, Downstream; Normal depth)
- Delineating river-cross-section

⇩

Hydrodynamic modelling

- Run unsteady flow analysis

⇩

Data Analysis

- Water level and depth determination
- Water calibration with past events
- Water profile lot
- Flood assessment

Figure 3.3 Data processing and HEC-RAS modelling

The required data set for this research has been gathered from different sources including previous field investigation report, remote sensing, published report, digitalized vector data and various agencies. River cross sections, part of floodplain areas and local settlement were obtained from satellite image and field investigation. 1D model hydraulic modelling strongly depends on geometric data as the main parameter and is a key to reliable simulation. Therefore, all cross sections were extracted from DEM and combined with the surveyed cross sections as a linked river network. Some of the DEM used is freely available from United States Geological Survey (USGS) website and others were created in QGIS platform by extracting contours from google earth. Final work of DEM extraction together with QGIS geometry resulted in 11 cross sections along Inkhu River, which than simulated in HEC-RAS 5.0.7. The stream flow of the extreme events was obtained from Osti and Egashira, 2009 as the unsteady flow input in HEC-RAS 5.0.7. The remainder of the data set such as actual flood level observation, inundation area, and damage loss were acquired through published literatures.

Figure 3.4 Inkhu River, main stream and flood path, (QGIS, 2019; Google Earth 2019)

Even though it was created in different context, the dam break equations (3.14) proposed by the National Weather Service (NWS) of the United States has been used to estimate the peak dam break flow, which is established on the concept of the falling head weir flow. The peak flow of the hydrograph can be compared with the resultant peak flow obtained by equation 3.14.

$$Q_w = Q_o + 3.1B_r\left(C/\left(T_f + C/\sqrt{H}\right)\right)^3 \qquad (3.14)$$

Here, the peak water flow = Q_w, the final average breach width (ft) = B_r, the breach flow and the non-breach flow $(cfs) = Q_o$, Coefficient that can be calculated as $C = 23.4 \times A_s/B_r$, reservoir surface area (acres) at the maximum pool level $= A_s$, the failure depth (ft) beyond the final breach elevation $= H$, the time to failure $= T_f$.

The equations developed by the Froehlich (1995) (where there were 63 dams breached ranging in height from 4 to 90 m have been investigated) is used to calculate the time of the breach.

$$T_f = 0.59\,(V_s^{0.47})/(H^{0.91}) \tag{3.15}$$

Here, T_f is the time of failure (h) that comprises the vertical erosion of the dam, V_s is the storage volume and the height (ft) of water above the bottom of the breach is H.

Since source and occurrence of other external component (earthquake and avalanches, any mass movement) and heterogeneity characteristics of the dam material and its surrounding have been ignored in this study. However, these external components may have contributed significantly to initiate the breaching process by producing huge outflow.

3.3.3 Result and discussion

The hydrodynamic flood modelling of the 1998's GLOF events that occurred at Tam Pokhari lake was performed using the HEC-RAS version 5.0.7 for one-dimensional steady flow analysis. The energy equation, using the standard step method, solved the steady flow, while Manning's equation and the contraction and expansion coefficients determined head losses. Eventually, analysis of river cross sections' behaviour under various flood discharges and water surface profiles for selected section of the Inkhu River was carried out. The hydro-dynamic modelling (HEC-RAS 5.0.7, 1D) was calibrated according to Manning's n values for both the channel and the floodplain.

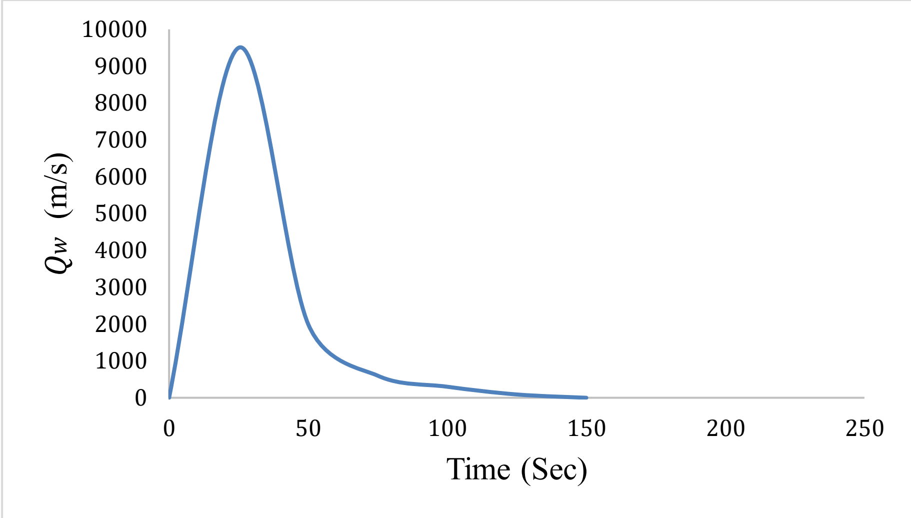

Figure 3.5 The HCE-RAS 5.0.7 produced breach hydrograph

The breach hydrograph was calculated using HCE-RAS based on estimated volume of the calculated by the dam break equation 3.14. Maximum peak discharge calculated was 9500 m^3/s which comply with HEC-RAS 5.0.7, produced dam breach hydrograph (Fig. 3.5). According to the equation 3.15 full breach formation time was about 45 minutes, which was also used for HEC-RAS5.0.7 modelling. According to an eyewitness, significant water jet lasted about half an hour at lake mouth (Fig 3.1).

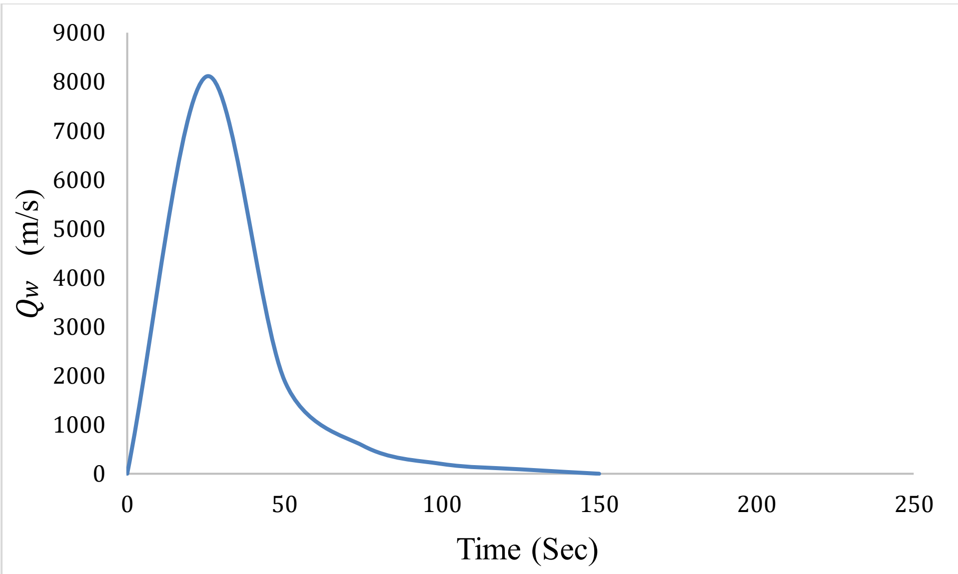

Figure 3.6 Calculated breach hydrograph

Outflow hydrograph at the end of the selected river section was calculated (Fig. 3.6). Water surface elevation of the cross sections are shown in Fig. 3.7. As it goes downstream the characteristics of the flood flow has been changed. This is due to the hydraulic pooling as flow passes through narrow cross-sections (Fig. 3.8). As a result, the impact of the GLOF was less significant as it travels further the downstream. The average calculated depth of the flood was 8m and at some point, it reached 25m.

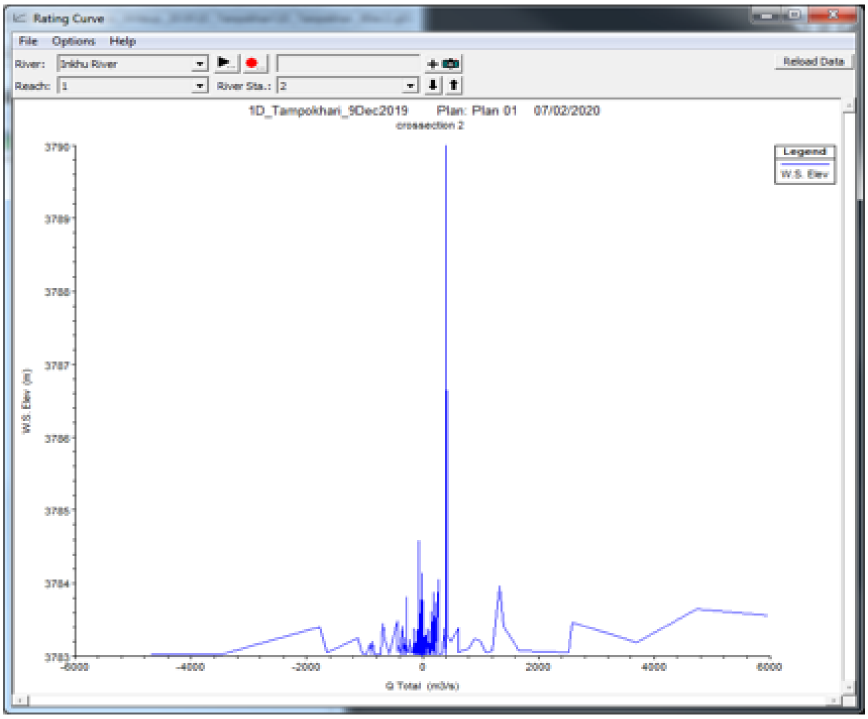

Figure 3.7 Water surface elevation, HCE-RAS

The result obtained by the water only flow modelling of Tam Pokhari GLOF does not reflect the true condition. The Tam Pokhari GLOF was very strong and damaging, the peak discharge was very high and the surveyed flood-level marks were also much higher than the calculated values. Because it was primarily dominated by a large flow of sediment that mainly developed after the flood water eroded the river bed and formed debris flow. Hence, to get the true extent of the damage it is necessary to reproduce the flow process by taking accountability of sediment discharge (Q_s).

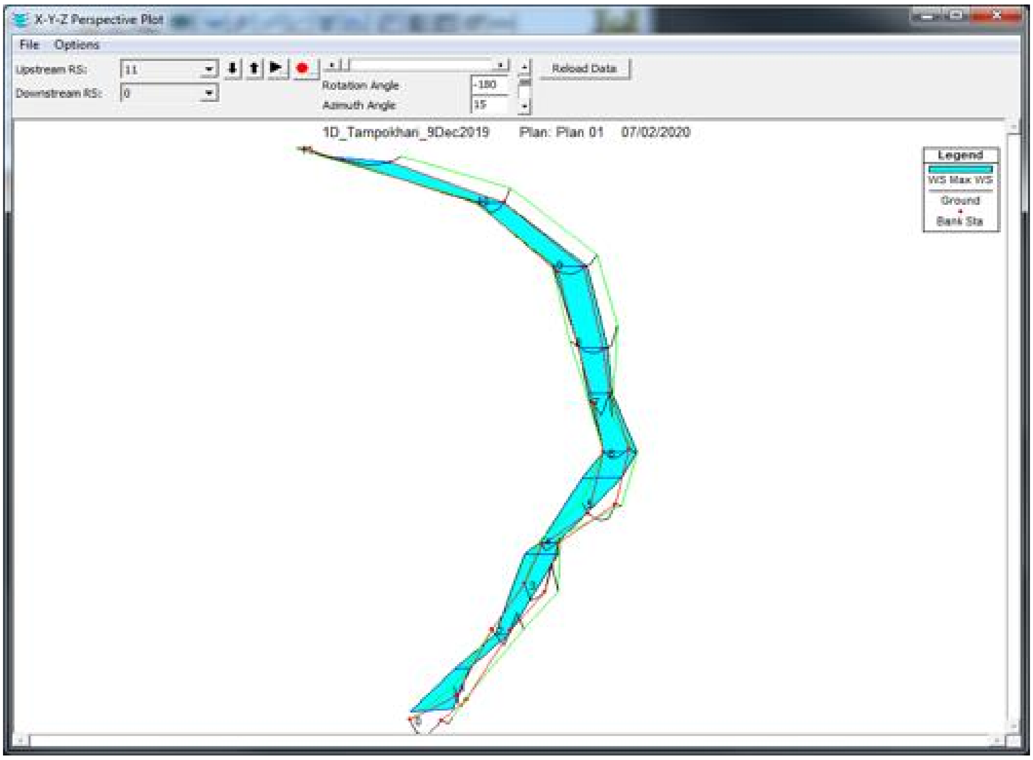

Figure 3.8 Cross-section in Inkhu river

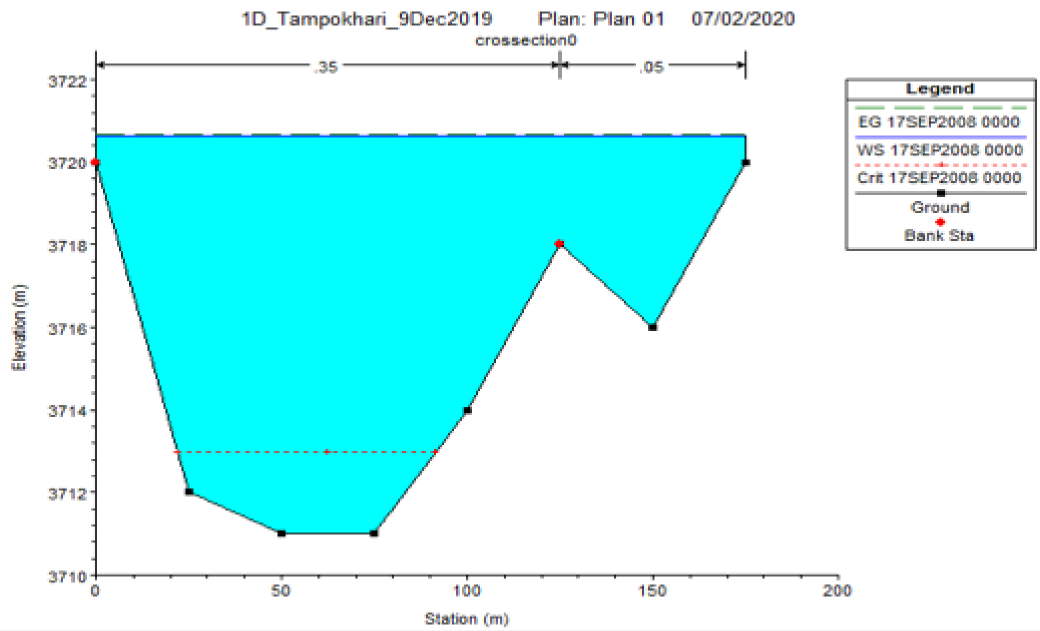

Figure 3.9 Flooded River station at Inkhu river due to GLOF

3.4 Downstream impact assessment

The mountains community has been suffering from glacial hazards particularly GLOFs, for many years. The adverse effect on the mountain infrastructure including roads, bridges, trekking trails, school, local lodges and hotels, villages, and agricultural land is very significant. At the same time human tragedy is highly likely. There is huge socio-economic impact when lives are lost or there are indirect impacts when people lose their livelihood e.g., when people lose their business, when all useful agricultural land is filled with debris. The data shows that on average every three to ten years there is a recorded GLOF event with varying degree of economic impacts (ICIMOD, 2010). Thus, systemic hazard assessment of the most GLOF-prone region is essential to evaluate the socio-economic effects and counter measures to minimize the adverse effects to downstream.

The GLOF that occurred in 1981 at Zhangzangbo in Tibet (China) caused huge destruction on both the China (Tibet) side as well as Nepal, including the Phulping and Friendship bridges in Nepal at Nepal-China highway that cost USD 3 million to rebuild (ICIMOD, 2011). Namche hydropower plant (USD 1.5 million) and another valuable mountain infrastructure were destroyed by the GLOF which originated from Dig Tsho (lake) at 1985 in Nepal (Vuichard and Zimmerman, 1987). The risks from these lakes or newly formed glacial lakes are still looming in some areas. So glacial hazard mitigation in these areas is essential but in-depth cost benefit analysis and participation of the regional stakeholder is vital to achieve community resilience and sustainable development. In terms of GLOF hazard mitigation, assessment of tangible benefit is hard to define but reduced damage can be considered. However, frequency of the reduced damage is difficult to determine due to lack of continuous monitoring and data. In this region, one cannot simply predict the timing and occurrences of GLOFs. It is very problematic to simulate numerically the inundation level and flow velocities at given time and space. There are various ways to assess the damage caused by the GLOF.

3.4.1 The damage cause by the past GLOF in Nepal

The GLOF has been reported in Nepal Himalaya and surrounding for more than three decades. Some of GLOFs have originated from the bordering Tibet (China) but affected Nepal also and vice-versa. Those reported events have adverse effects on livelihood and local settlement. So, in this section the downstream impact of the recorded GLOF events at Himalayan region is explored.

3.4.1.1 Pokhara valley

It is estimated that the Pokhara valley suffered a GLOF 500 years ago (ICIMOD, 2010). It is believed that the debris flow has been started from Machhapuchhare area. Also, the thick sediments (50-60 m) at the floor of the Pokhara Valley are an indication of the debris flow in the past. The damage caused by the GLOF is known.

Figure 3.10 Pokhara Valley (Stecker, 2020)

3.4.1.2 Barun Khola

The official survey by Government of Nepal, Survey Department at 1992 reveal that the GLOF has occurred at Barun Khola valley. The official aerial photograph shows that the evidence of the GLOF originated at Barun Pokhari. The precise date of the GLOF and other damages caused are unknown.

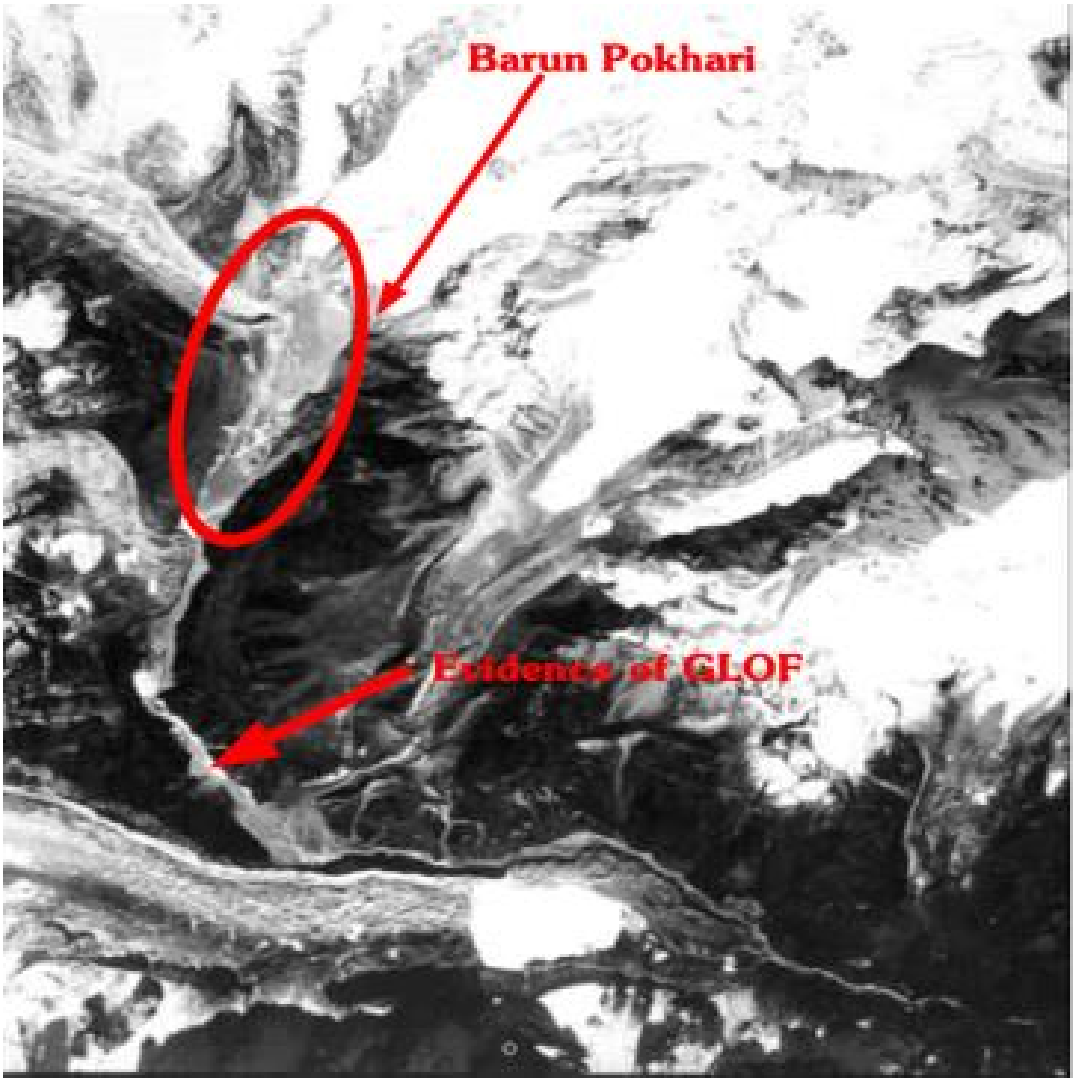

Figure 3.11 Barun Pokhari GLOF (HMD Nepal, 2018)

3.4.1.3 Gelhaipuco

The end moraine-dammed glacial lake, Gelhaipuco is located in Tibet bordering in Nepal at geographic position of latitude 27° 58' N and longitude 87° 49' E, East of river of Riwo, Dinggye County. Chinese Academy of Science reported that the GLOF occurred on 21st September 1964 due to ice avalanches. It was also reported that there was high precipitation rate in the Natangqu River Basin between March to September in 1964, which caused the glacier of the Natangqu River to slide (LIGG, 1988) into the lake and that generated large amount of a shock wave and water level increase. Ultimately, the lake water overtopped through the moraine dam and breached the 30m steep valley through the dam. As of 2014 the water level is lower than the 1964 preflood water level (Che, Xiao and Liou, 2014). Che, Xiao and Liou, 2014 reports that glaciers in the basin lost 19% of total area since the 1970's and that the retreat rate increased in the 2001-2013 period.

It was reported that the flood with significant debris flow caused huge damage to people's livelihood with economic loss to both China (Tibet) and Arun valley in Nepal. It damaged Chentang-Riwo Highway and 12 trucks transporting timber which were washed away (ICIMOD, 2010). According to the ICIMOD (2011) before the burst, Gelhaipuco Lake was 1.4 km in length and 0.548 km^2 and the water level of the lake decreased by 40 m after the lake burst in 1964 and discharged about 23.36 million m^3 of water. The slope of the exposed lake bed is 0.6% and it is 0.2 km away from the glacier margin. Satellite image reveals that the present condition of the lake is stable. But if the glacier advances again, the possibility of another burst is likely. The field photograph and satellite image reveal the changes that occurred on the Gelhaipuco Lake.

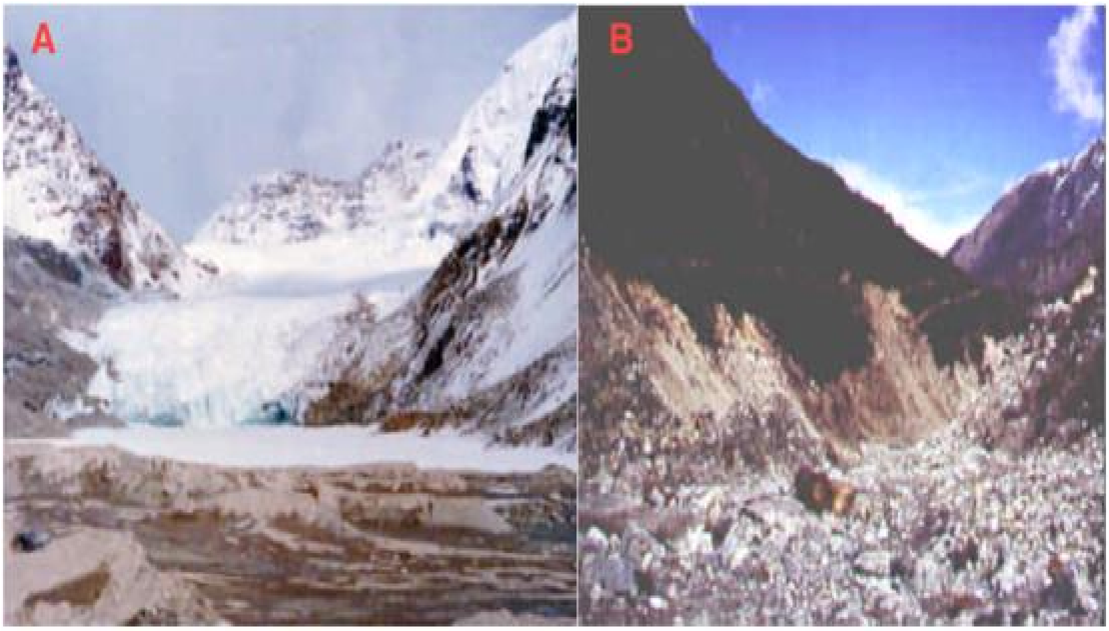

Figure 3.12 A) Gelhaipuco Glacial Lake shows the lake in contact with the hanging glacier, B) Bank of the Natangchu (tributary of the Arun River in China, Tibet) eroded after the Gelhaipuco GLOF in 1964, both pictures were taken in 1987 (ICIMOD, 2010b)

Figure 3.13 The Gelhaipuco Glacial Lake area is shown in the yellow circle on 22 September 1988 (ICIMOD, 2010)

3.4.1.5 Zhangzangbo-Cho

Zhangzangbo-Cho is moraine-dammed glacial lake located at Poiqu (Bhote-Sun Koshi) River in China (Tibet). ICIMOD (2011) reported that on 11^{th} July 1981 the Zhangzangbo-Cho Lake suddenly burst due to ice avalanches at midnight forming a wide breach with 50m deep and 40-60m bottom width was formed at the moraine (ICIMOD, 2001). According to Xu Daoming (1985), the largest burst discharge was about 1,6000 m^3s^{-1} which happened 23 min after the burst which formed a large alluvial fan. During the 60 minutes of the breaching event, it was estimated that 19 million m^3 water and about 4 million m^3 of sediment was discharged. End moraine-dammed glacial lake was reduced to 1.1 km from 1.7 km and to 0.265 m^2 from 0.643 m^2 after the breach. There had been a burst in 1964 from the same lake, but the breach was different from that in 1981. The burst discharge and the damage caused were smaller.

Figure 3.14 The washed away portion of Nepal-China (Kodari) Highway damaged by 1981 GLOF, B. Damaged pier of the old bridge by 1981 GLOF and New bridge at Kodari highway (ICIMOD, 2001)

This GLOF has huge economic loss to both China and Nepal side. The debris flow destroyed the several highway sections including outlet of Zhangzangbo Gully and the Sun Koshi Power Station in Nepal, the diversion weir at the Sun Koshi hydropower plant in Nepal, few bridges including Friendship Bridge of the China–Nepal Highway, and destroyed extensive road sections of the Arniko Highway of Nepal amounting to losses of USD 3 million. The washed-out portion of the Kodari Highway is shown in Fig. 3.14.

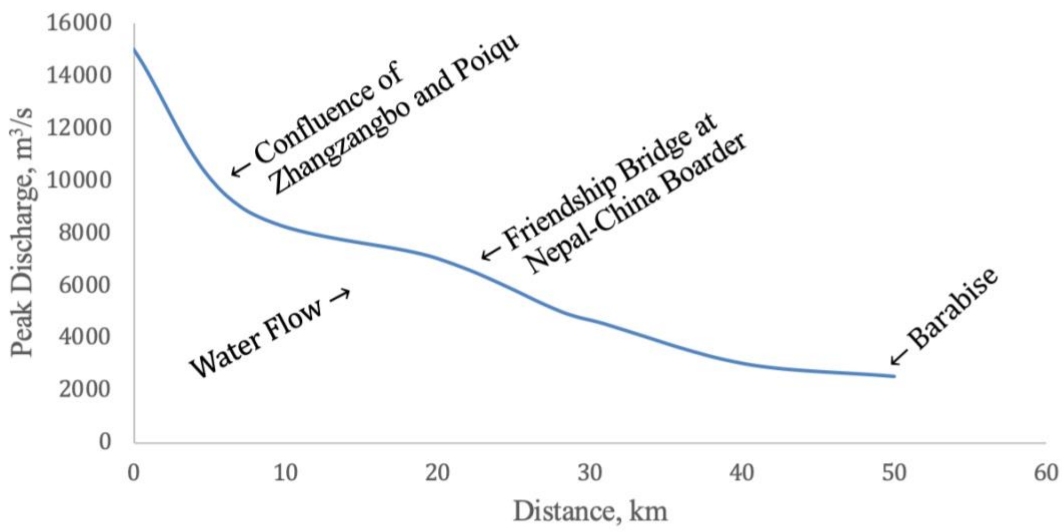

Figure 3.15 GLOF from the Zhangzangbo Glacial Lake, Poiqu River, Tibet (China) or the Bhote (Sun) Koshi (Nepal), Peak discharge attenuation downstream, (Modified from Xu Daoming, 1985)

3.4.1.6 Nare GLOF

Nare glacial lake was formed due to damming of the ice cored moraine where melted glacial water deposited gradually over the year. It is situated in the Dudh Koshi basin on the Southern slope of the Ama Dablam mountain Nepal. According to ICIMOD (2001) the GLOF occurred at 3 September 1977. This caused catastrophic damage to the downstream flood plains. According to ICIMOD report the GLOF the road, bridges, and farmland in Nepal (ICIMOD, 2009).

3.4.1.7 Nagma GLOF

Nagma Pokhari glacial lake is situated at the Tamor watershed, Nepal. According to ICIMOD, 2001 report the GLOF that occurred on 23 June 1980 was devastating to the local community. The entire village in the flood plan had to be relocated. It also destroyed several road and other mountain infrastructure.

The 1992 aerial photographs of Nagma Glacial Lake are shown in (Fig. 3.16). In this figure, the eroded banks of the Tamor River after the Nagma GLOF of 1980 can be seen.

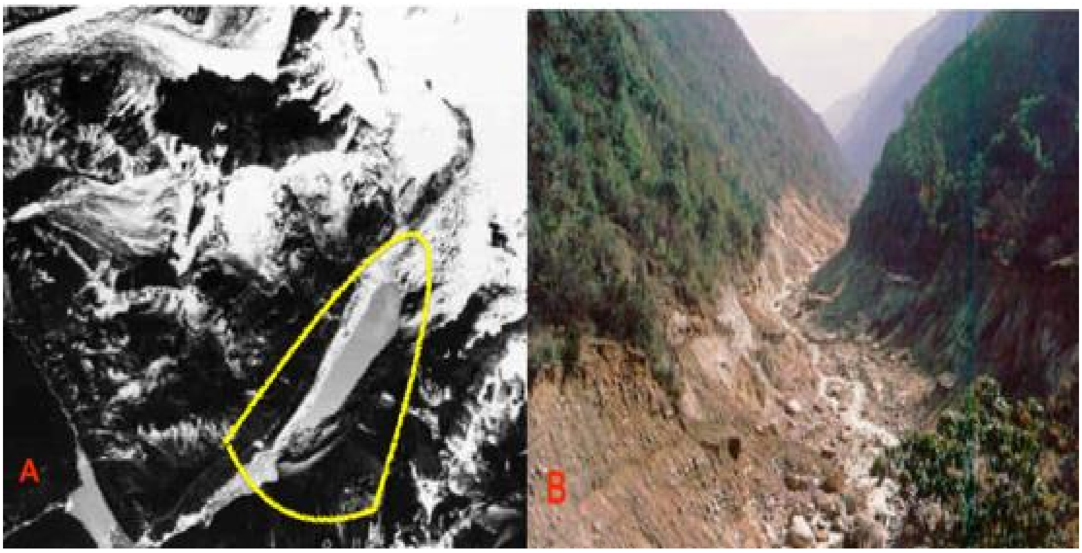

Figure 3.16 A) Glacial Lake after the GLOF of 1980 (Aerial Photo 53-56) by Survey Department of Nepal B) The eroded banks of the Tamor River after the Nagma GLOF of 1980 (Carson, 1985).

3.4.1.8 Jinco GLOF

Jinco is end-moraine glacial lake situated at the headwaters of the Yairuzangbo river of the Pumqu Basin China (Tibet) and the Arun Basin in Nepal. The GLOF was recorded on August 1982. The cause of the outburst may have been the dry and hot weather, as well as strong glacial ablations that seeped melting water into the glacier bed that helped it to slide. The shock wave generated from the collapse of the ice block damaged the moraine dam that resulted in the GLOF.

The debris flow caused huge damage to the downstream flood. It was reported that 1,600 livestock were lost, about 19 hectares of agricultural land was lost, eight houses were destroyed and Gujing village in Tibet suffered destruction (Mool et al., 2001).

3.4.1.9 Dig Tsho GLOF

Dig Tsho (Langmoche) is Glacial Lake in the Dudh Koshi Basin, Nepal. It is contact with Langmoche hanging glacier which experienced GLOF at 1985 August. The GLOF was devastating to the community. It destroyed the almost completed Namche Hydropower Plant (estimated loss of USD 1.5 million), 14 bridges, trails, agricultural land. It was also reported that many lives were lost (ICIMOD, 2001). Figure 3.17 is a photograph taken after the GLOF of 1985, which shows the remnants of Dig Tsho Glacial Lake and Langmoche Glacier.

Figure 3.17 Birds-eye view showing the post-GLOF Dig Tsho Glacial Lake, Langmoche Glacier at the slope and the debris along the gully after the GLOF of 1985 (WECS, 1995a)

3.4.1.10 Chubung GLOF

Chubung glacial lake is situated in the Tama Koshi basin at Rolwaling valley Nepal. Which is connected to Ripimo Shar glacier. Chubung glacial lake suffered a GLOF on

12 July 1991 that damaged many houses and damaged agricultural land in the Rowaling valley. Post Chubung GLOF picture at Fig. 3.17, shows the breaching of the moraine dam and deposited fan.

Figure 3.18 The breaching of the moraine dam and fan deposited after the Chubung GLOF of 12 July 1991 in the Rolwaling Valley, Nepal (ICIMOD, 2001)

3.4.1.11 Tam Pokhari GLOF 1998

Tam Pokhari glacial lake is situated at the tongue of the Saba glacier in the headwater of the Inkhu Khola of the Dudh Koshi Sub-basin Nepal. It burst on 3 September 1998. It caused large damage to the community downstream. It was reported that two lives were lost, four suspension bridges and two wooden bridges were damaged, and farmland was buried. The total loss of property is estimated to be worth NRs 150.66 million. Details of this GLOF have been investigated and modelled in previous chapter.

3.4.2 Erosion and sedimentation at downstream flood plain

In most of the cases the GLOF has persistent socio-ecological and socio-economic impact to the region. Often, post-GLOF erosion and sedimentation are considered as secondary hazard to the region (Vilímek et al., 2015). During a GLOF, the flow velocity and discharge are exceptionally high and it becomes practically impossible to carry out any measurement. Field observations after a GLOF event have shown a much higher sediment concentration of rivers than before the GLOF event (WECS, 1995a). The total sediment load is generally accepted as the wash load, which moves through a river system and finally deposits in deltas. Currently, no measurements have been taken of total sediment during GLOF events in Nepal. However, average estimates of total load during torrents can be made assuming a high sediment concentration (WECS, 1987b). The flow velocity and particle diameter can also be used to analyse the size of boulders that can be moved during the GLOF events.

As it has been mentioned in the previous section, Dig Tsho GLOF 1985 originated form Dig Tsho glacial lake (4,400 m a.s.l) caused huge distractions to the downstream. It damaged newly build hydro power station, 30 house and 14 bridges and that shipped 900,000 m^3 of debris further 2 km down from the point of breach and dumped in the valley (Vuichard & Zimmermann, 1986) (Fig. 3.17). Sedimentation and erosion of the downstream flood plain depend on the various geomorphology of the area. The sedimentation and erosion based on the U-shaped, V-shaped valley and downstream impact will be assessed blow.

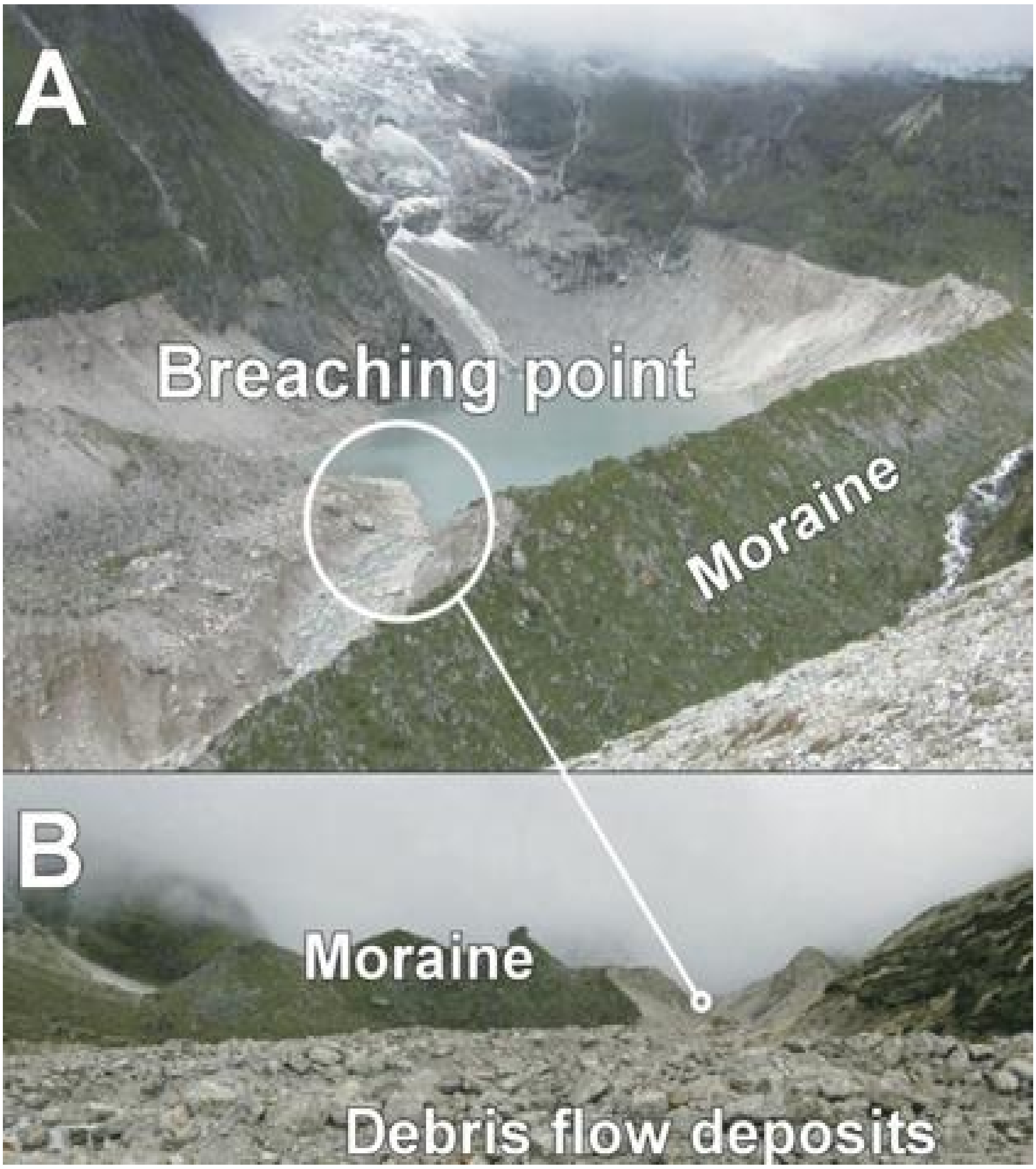

Figure 3.19 A) Dig Tsho GLOF 1985 dam breach B) Sedimentation and deposition due to debris flow (Umemura, 2002; Higaki and Sato, 2012)

3.4.2.1 U-shaped valleys

During the GLOF process, the sedimentation and erosion took place simultaneously. Normally, the floodplain and riverbed slope gradients are gentle in U-Shaped valley compared to V-shaped valley. Due to this phenomenon the sediment (debris) travels relatively short distance from the Main Boundary Thrust (MBT) during the GLOF. The rate of erosion will depend on the various factors including geomorphology of the area.

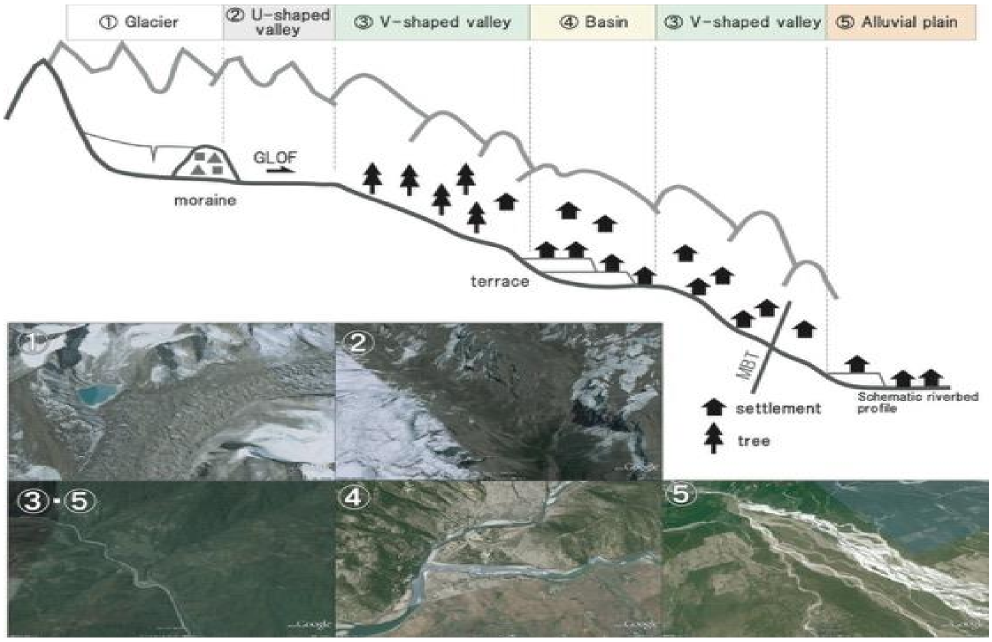

Figure 3.20 Schematic diagram of main river and their topographical segments (Higaki and Sato, 2012)

The discharge from Nare glacial lake (Nepal) during 1977 GLOF deposited near the confluence of the Bhote Koshi River. The sediments were characterized by randomly dispensed gravel of a various range of sizes and a convex shape through the transverse sections, clearly representing a debris flow (Higaki and Sato, 2012). Even after more than thirty years after the GLOF area has not been recovered (Fig. 3.20). These types of collapses are mainly dependent on the geomorphology of the area (U-shaped valley floor) which is formed by highly erosion-prone glacial deposits, fluvio-glacial deposits and thick river-terrace deposits from past glacial expansion (Higaki and Sato, 2012). GLOF may initiate the lateral erosion which may trigger the landslides. There has been a report that the deposit from previous glaciation have been stated to initiate the landslide along the Kali Gandaki River in the Mustang District, Nepal (Higaki, 2005). This is as a result of scouring erosion.

Figure 3.21 Collapsed banks in glacial deposits originated during the Nare GLOF (1977) Nepal, (Modified form ICIMOD, 2010)

3.4.2.2 V-shaped valleys

In the Himalayan region narrow V-shaped valley are dominant, created by river incision at lower segments of the U-shaped valley (Fig. 3.19). The downstream impact of the GLOF and characteristic of the flood flow are dominant due to the geological structure. The types of the geomorphology and its formation play important roles to determine the rate of erosion and the susceptibility of the materials that comprise river banks, roads and bridges. The GLOF may induce instability in these riverbed slopes due to lateral erosion because most of the deep-rooted landslide configurations are dispersed in the centre of the river reaches (Yagi, 1995; Higaki and Sato, 2012).

Figure 3.22 Temporary damming caused by the Dig Tsho GLOF (1985) Nepal (UNDP, 2017)

The Dig Tsho GLOF (1985) Nepal caused large-scale landslides along the outer bends of the valley (WECS, 1987). It has been claimed by a local witness that during the Dig Tsho GLOF, a temporary dam was formed around the constricted gorge at the confluence of Bhote Koshi and Dudh Koshi, that was eventually breached (Fig. 3.20). This is evident as Higaki and Sato (2012) reports that the size of debris deposited downstream measuring 1 to 1.5 metres among the fine sand stratification. The bridges at the downstream of the river collapsed about 30 to 50 minutes after the GLOF (Bajracharya et al., 2007). This may have been caused by the breaching of the temporary dam where in this segment of the river it is capable of producing woody debris, as this forest exist along the valley.

It has been reported that the 2016 GLOF at Bhota Koshi river in Nepal triggered a landslide (Fig. 3.23) along the valley downstream that damaged hydropower plant and other mountain infrastructure on its path downstream (Kornei, 2020).

Figure 3.23 Aftermath of a landslide near Tatopani, Nepal, triggered by July 2016 GLOF at Bhote Koshi, Nepal (Kornei, 2020)

3.4.2.3 Basin and alluvial plains

Traditionally most of the river basin around Himalayan region has been used as agricultural land as it comparatively more fertile and has easy access to irrigation. In Nepal also most of the glacial originated river basin are highly populated and land are extensively used for agricultural purpose. These lands are highly vulnerable to problem caused by the GLOF including sedimentation and erosion (Fig. 3.24). As we go towards the Terai Plain (alluvial plains) in Nepal the sandy and silty material sedimentation is a prominent character of the floods. Mostly, the riverbed slopes are extremely gentle in these segments of the river as a consequence of frequent course changes and riverbed aggradations which can be anticipated along the river (Higaki and Sato, 2012). This will have adverse effect on the local community and stakeholders.

Figure 3.24 Ruined rice paddies, covered by up to 45 cm of sand where Budhi Kulo (irrigation channel) spilled sediment-clogged bed in Nepal (Gladfelter, 2020)

3.4.3 Lake volume calculations; empirical formulae

It is vital to investigate historical GLOF events and analyse the empirical relationship between lake volume and outburst peak discharges in order to mitigate GLOF hazard. Several formulae already exist that relate lake area and volume from different parts of the world, which warrants further analysis to implement in this research scenario. Due to the variation of geographical terrain and other various factors ice and moraine-dammed glacial lakes often have different geometries (McKillop and Clague, 2007) and therefore different volumes.

This research collected data of moraine-dammed lakes worldwide and derived the empirical formula to calculate lake volume of a glacial lake in Hindu Kush Himalaya Region (particularly Mt. Everest Region, Nepal).

This research has collected the following outburst details from Patagonia, Chile and Swiss Alps up to the present.

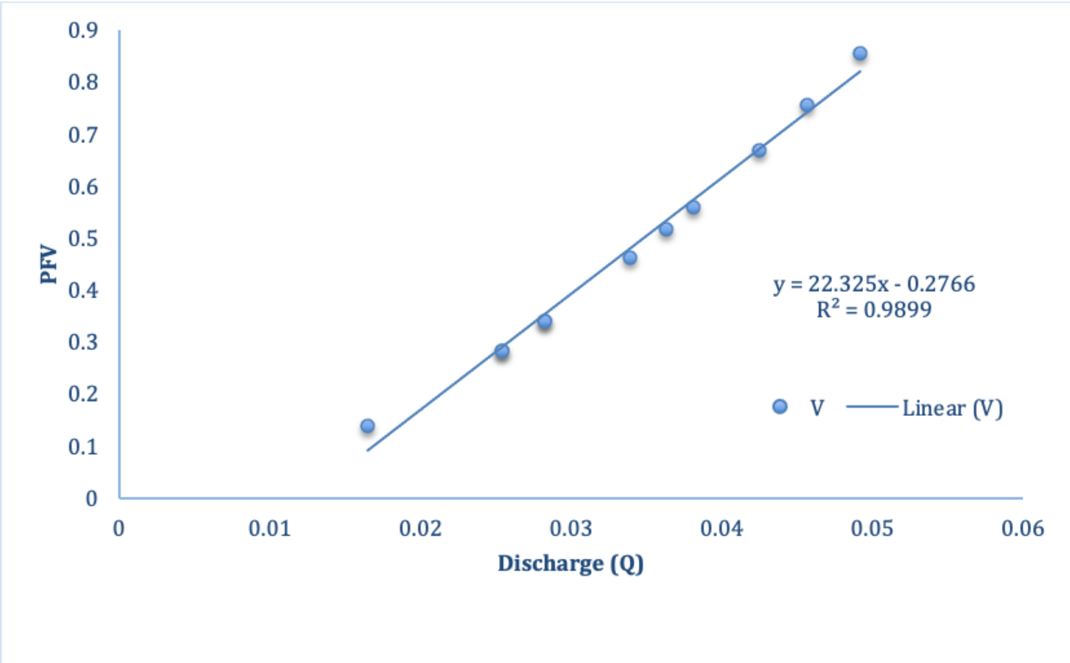

Figure 3.25 Discharge vs potential volume of the lake's Himalayan Glacial Lake

Swiss Alps (Huggel et al. 2002)

$$D = 0.104A^{0.42}, r^2 = 0.916 \quad (3.16)$$

Where area (A) and mean depth (D), including a bias correction

The lake volume (V) is then calculated as follows

$$V = 0.104A^{1.42} \quad (3.17)$$

Details of the failed lakes in historic time

Table 3.1 Details of the failed lakes in historic time (Huggel et al., 2002)

Lake	**Type of lake**	**Reference**	**Area (m^2x10^6)**	**Volume (m^3x10^6)**	**Mean depth (m)**
Ice Cave Lake	Ice-dammed	Maag, 1963	0.0035	0.01	2.9
Gruben Lake	Thermokarst	Teysseire, 1999	50.01	0.05	5.0
Crusoe-Baby	Ice-dammed	Maag, 1963	0.017	0.08	4.7
Gruben Lake	Ice-dammed	Kääb, 1996	30.021	0.15	7.1
Gruben Lake	Moraine-dammed	Kääb, 1996	10.023	0.24	10.4
MT' Lake	Ice-dammed	Blown and Church, 1985	0.042	0.50	12.0
Lac d'Arsine	Moraine-dammed	Vallon, 1989	0.059	0.80	13.6
Nostetuko lake	Moraine-dammed	Clague and Evans, 1994	0.262	7.50	28.6
Between Lake	Ice-dammed	Maag, 1963	0.400	7.50	18.8
Abmachimai Co	Moraine-dammed	Meon and Schwarz, 1993	0.565	19.4	34.3
Gjanupsvatn	Ice-dammed	Costa and Schuster, 1988	0.600	20	33.3
Quongzonk Co	Moraine-dammed	Meon and Schwarz, 1993	0.753	21	27.9
Laguna Parón	Moraine-dammed	Lliboutry et al., 1977	1.600	75	46.9
Summit Lake	Ice-dammed	Mathews and Clague, 1993	5.0	250	50.0
Phantom Lake	Ice-dammed	Maag, 1963	6.0	500	83.3

Patagonia, Chile- (Iribarren Anacona, Norton and Mackintosh, 2014)

$$V = 31.249A^{1.3399} \quad (3.18)$$

$$Q_{max} = 0.054V^{0.66} \quad \text{(Walder and O'Connor, 1997)} \quad (3.19)$$

Where the lake volume is V, peak discharge is Q and A the lake area is A.

Note: - Dam breach peak discharge estimates can have uncertainties of up to ±1 order of magnitude (Wahl, 2004) and error of the volume estimates was ±71%.

Swiss Alps (Huggel et al. 2002)

$$V = 0.104A^{0.42}, \text{where } r^2 = 0.916 \quad (3.20)$$

$$Q_{max} = 0.00077V^{1.017},\ r^2 = 0.94 \quad (3.21)$$

(Where area A, mean depth D and the lake volume V)

Himalayan glacial lake, Nepal (this study)

$$V = 0.104A^{0.94}, \text{where } r^2 = 0.991 \quad (3.22)$$

$$Q_{max} = 0.00077V^{0.9},\ r^2 = 0.999 \quad (3.23)$$

(Where is the lake volume V, peak discharge Q and the lake area A)

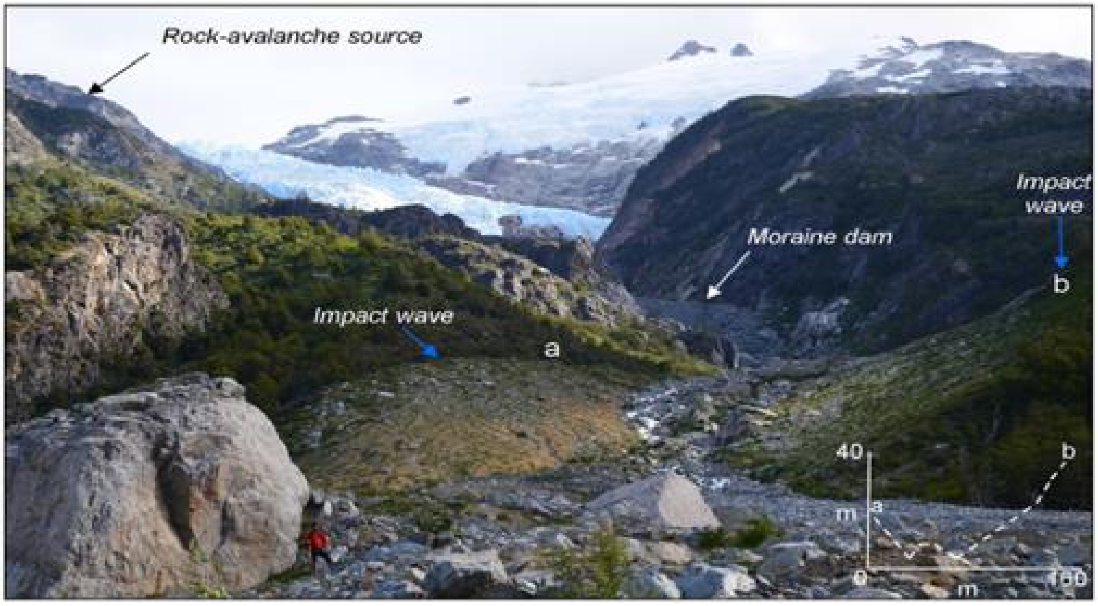

Figure 3.26 Geomorphic effects of a rock avalanche induced GLOF, Impact of the wave (a), elevated traces of impact wave (b), graph show the cross-section of the outlet (Iribarren, Norton and Mackintosh, 2014).

3.5 Conclusion

As global temperature is predicted to increase continuously in coming years the GLOF flood is a great concern to the global communities. This chapter investigated the characteristics of the GLOF flood flow and their impact to the downstream community and the flood flow behaviour at different geomorphological floodplain (U-shaped valley, V-shaped valley and basin). The debris flow often incur huge impact to expensive mountain infrastructure and livelihood. The 1998 Tam Pokhari GLOF was modelled using HEC-RAS 5.0.7.

Debris mixed (water-sediment) and water-only flow behaves differently. Moreover, the flow behaviour varies in time and space during the flood and also river geometry and local geomorphology play important roles. In case of the water-only flow, it has less impact downstream as peak flow attenuation occurs in short distance. The Tam Pokhari GLOF caused huge distraction due to sediment transported by the debris flow. The GLOF flow may behave as debris flow from the point of breach and as it goes further down, peak flow discharge may increase. This may also cause substantial erosion and sedimentation downstream. Erosion and deposition during the GLOF take place alternatively, as sediment deposited along the course of the river bank the flood flow continue downstream and cause further damage. Debris flow causes the more damage downstream than the water only of mixed flow.

Socio-economic loss of the GLOF at mountainous community around the world is grave concern. Many lives have been lost and millions of dollars' worth of mountain infrastructure have been destroyed. It has also destroyed agricultural land at river basin and downstream floodplain. The root cause of the GLOF is glacial lake and its behaviour which is dynamic in nature. Hence, it is essential to monitor regularly the GLOF-prone region according to topography, geology, glaciology, environmental and socio-economic characters as well as various geo- hazardous conditions.

Chapter 4

Identifying vulnerability factors and conditions of GLOF

Since the 1960s the number of glacial lake formation and expansion has increased in Himalayan region Nepal. The escalation in temperature since 1970s also helped with the continued rise in glacier retreat and glacial lake formation (Bolch et al., 2008). The rising trend continues and this increases the possibility of a GLOF hazard (Shrestha and Aryal, 2011). As of 2017 there are 1541 (80.95±15.25 km^2) glacial lakes within the Himalaya region, Nepal (Khadka et al., 2018). Hence, studies of the glacial lakes are important in Nepalese Himalaya as they are primary source of catastrophic GLOF that have destroyed many lives and property and caused huge economic loss. They have also destroyed hydropower plants and expensive infrastructures (Richardson and Reynolds, 2000).

GLOFs can occur through diverse mechanisms as creation of the glacial lake and its failure is a dynamic process. It involves various stages, but most commonly the glacial lake fails due to the progressive enlargement of a dam breach. The overtopping of the dam, piping, intensive rainfall, mass movement (ice/rock avalanches) may trigger the GLOF. The piping failure post-earthquake, mechanical failure of the moraine dam (ice-core) and surge wave from the landslide on the side wall of adjacent lake are also related to GLOF. Therefore, a systemic and scientific investigation of the glacial lake and its vulnerability is necessary to minimize or eliminate the potential risk of losing many lives and infrastructure. This chapter has examined and modelled the vulnerability factors and conditions of the glacial lake that makes it susceptible to GLOF, based on empirical evidence and data obtained by remote sensing and satellite imagery (e.g., Landsat).

4.1 Introduction

There have been numerous studies conducted to understand glacial lake outburst hazard around the world (e.g., Benn & Evans, 1998; Clague & Evans, 2000; Wang et. al., 2011; Clague & O'Connor, 2015). However, in the Himalaya region, data about failed glacial lakes have not been systematically analyzed yet, especially the causes and mechanisms of glacial lake failure and its vulnerability factors remain mostly unknown. It is very challenging to obtain spatial parameters of the glaciers and glacial lakes including length, width and depth, and the rate at which they change their shape due to the extreme geographic condition of the Himalaya region.

To identify the common cause of GLOFs in high Himalaya region and to explore glacial lake vulnerability factors this chapter analyses the data collected by extensive literature review and examines the satellite data (Landsat). Remote sensing is considered as the best way to investigate glacial lakes and the impact of GLOFs in the remote mountainous region (Bolch et al., 2011) because it allows rapid analysis of the large, glaciated region in an economical way (Huggel et al., 2002). It will also provide significant resources to study the geomorphology of the remote area particularly these high Himalayan glacial lakes and build a comprehensive framework to carry out the vulnerability assessment of glacial lakes. This will also help to improve the understanding of the glacial hazard dynamics and improve resilience.

It is essential to examine the vulnerability of the glacial lake(s) and surrounding to understand the GLOF hazard dynamics. There have been more than 30 GLOFs events recorded in the Hindu Kush Himalaya region since 1930, among them 14 GLOF events affected Nepal and surrounding areas. This chapter investigates only 11 of them (Table 1) which can be precisely located and mapped to develop a comprehensive framework to understand glacial lake vulnerability based on remote sensing and various published data sets.

4.2 Study area

Nepal is home to the top ten highest mountains in the world (except Mount K2, second Highest Mountain). It spans between 26° 15’ to 30° 30’ N latitude and 80° 00’ to 88° 15’ E longitude with an area of 147,181 km^2 and the average width of 180 km in rectangular shape. Nepal shares a border with China (Tibet) in the north and India in the South, East and West. It is also one of the highly glaciated regions within the Hindu Kush Himalaya region (Fig. 4.1) from where all the major rivers in the region including Ganga, Brahmaputra, and Indus originate.

Nepal lies between two tectonic plates and this makes it an active seismic zone. In 2015, Nepal experienced a significant earthquake (M 7.8 Richter scale) that caused 10 billion USD damage and more than 9,000 people lost their lives. There was also some damage caused to the neighbouring countries including India, China and Bangladesh. Nepal has a substantial altitudinal variation varying from 64 m above mean sea level in the Southeast region to world highest point, Mt. Everest at 8850 m above mean sea level in the north within the range of 150 km. It is the most extreme land-based relief in the world. Due to this vast elevation difference, geomorphological condition, soft-soil cover, intense monsoon rainfall and steep river gradient. this region is prone to various natural hazards. Flooding, landslide, avalanches, glacial lake outburst flood, and drought are common phenomena to this region.

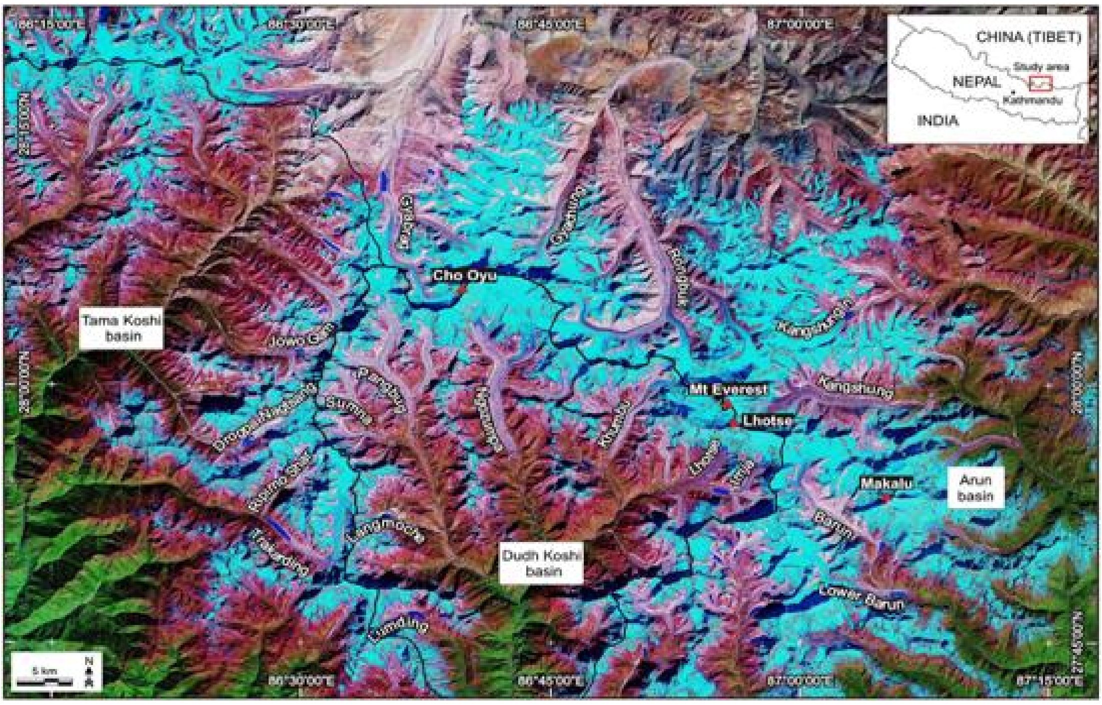

Figure 4.1 Heavily glaciated Mt Everest region, Nepal; Landsat image (Modified from Benn et al., 2012)

Himalaya region is critical to the natural hazard particularly glacial lake outburst (Bajracharya and Mool, 2009). Catastrophic floods due to the outburst of glacial lakes have been recognized as one of the primary natural hazards in Nepal, making downstream areas vulnerable. GLOF is a dynamic process as it involves the occurrence of a complex phenomenon. It varies from place to place depending on the geomorphological setting of the area, lake geometry, dam material and other external factors (earthquake, substantial precipitation). Monsoon rainfall commonly triggers a variety of slope movements, many of which cause extensive damage to life and property. So, this research investigated 11 GLOF events out of 14 events (Table 1) recorded within Nepal boundary but affected both Nepal and China (Tibet) in some way, resulting in GLOFs. This study will help to investigate the vulnerability factors of these glacial lakes prone to disaster.

4.3 Measuring and modelling vulnerability factors and condition

This research utilizes remote sensing data (Landsat imagery), DEM, topographic maps, geographic information system (QGIS) and different literatures to qualitatively evaluate the 11 historical GLOF events in HKH region that affected Nepal (some originated from Tibet) including, Tam Pokhari GLOF, 1998, Mt. Everest Region Nepal.

Remote sensing is one of the suitable methods for monitoring glacier and surrounding in large scale. Different spectral reflectance of the glacier and surrounding help them to characterise in satellite imagery. Landsat 7 and Landsat 8 images have been used to obtain morphometric parameter of the glacial lake and surrounding. Least cloud cover Landsat images taken between 2000 and 2009 (each year) were selected and acquired with 15 m spatial resolution. Google earth maps also used to extract the ground control point.

To obtain spatial information of the lake and surrounding, DEM is created where the historical events was occurred. The Shuttle Radar Topography Mission (SRTM) provides 90 m resolution data. Topography map (prepared by Army Map Services (RMBP), Crops of Engineer, US Army, Washington, 1955) and Global Digital Elevation Model have also been used to derive the glacier parameters which are used for reference purposes.

Table 4.1 Historical GLOFs originated within Nepal, (Modified from ICIMOD 2010, Bajracharya et al., 2009)

Date	River Basin	Lake	Location		Origin/ Country affected
			Latitude	Longitude	
450 years ago	Seti Khola	Machhapuchhare	28° 31’ 13”	83° 59’ 30”	Nepal
3 Sep 77	Dudh Koshi	Nare	27° 49’ 47”	86° 50’ 12”	Nepal
23 Jun 80	Tamor	Nagma Pokhari	27° 51’ 57”	87° 51’ 46”	Nepal
4 Aug 85	Dudh Koshi	Dig Tsho	27° 02’ 36”	86° 35’ 02”	Nepal
12 Jul 91	Tama Koshi	Chubung	27° 02’ 37”	86° 27’ 38”	Nepal
3 Sep 98	Dudh Koshi	Tam Pokhari	27° 44’ 20”	86° 50’ 45”	Nepal
Unknown	Arun	Barun Khola	27° 50’ 33”	87° 05’ 01”	Nepal
Unknown	Arun	Barun Khola	27° 49’ 46”	87° 05’ 42”	Nepal
Unknown	Dudh Koshi	Chokarma Cho	27° 54’ 21”	86° 54’ 48”	Nepal
Unknown	Kali Gandaki	Unnamed (Mustang)	23° 13’ 14”	83° 42’ 09”	Nepal
Unknown	Kali Gandaki	Unnamed (Mustang)	29° 07’03"	83° 44' 19"	Nepal

4.3.2 Methodology

In this research, glacial lake vulnerability factors are mainly divided into two. The first is the geomorphic condition (dam, host glacier and surroundings) and the second is the different triggering factors that occur mainly due to gravitational and meteorological events. Several variables have been used to identify hazardous moraine-dammed glacial lakes in different parts of the world. The dam geometry (e.g., width-to-height ratio, flank steepness and dam freeboard) and internal structure (e.g., presence of ice and particle size distribution) are probably the most critical conditioning factors of outburst floods (Richardson and Reynolds, 2000a). Nonetheless, these characteristics of the dam can only be measured precisely in the field or by using high-resolution satellite images of all areas. It is out of the scope of this research to investigate each of the past GLOF events in the area and obtain high-resolution data. Moreover, it seems unviable to investigate each lake in the field, taking into consideration that the remoteness and harsh weather conditions may hamper the measurements on the ground.

This research selected few characteristics of glacial lakes which include dams, their surroundings and conditioning factors (Fig. 4.2). These characteristics can be measured and modelled using medium-resolution satellite images and recorded meteorological dataset. We have applied few criteria to select these variables including the reproducibility of variables from each other (has to be independent variables) and factors from the historical events. The following variables met the aforementioned criteria including mean slope of the dam (S_D), distance between lake and glacier terminus (D), slope between lake and glacier terminus (S_L), area of the lake (A_L), area of the host glacier (A_G), extreme weather (rainfall, R) and seismic events (S).

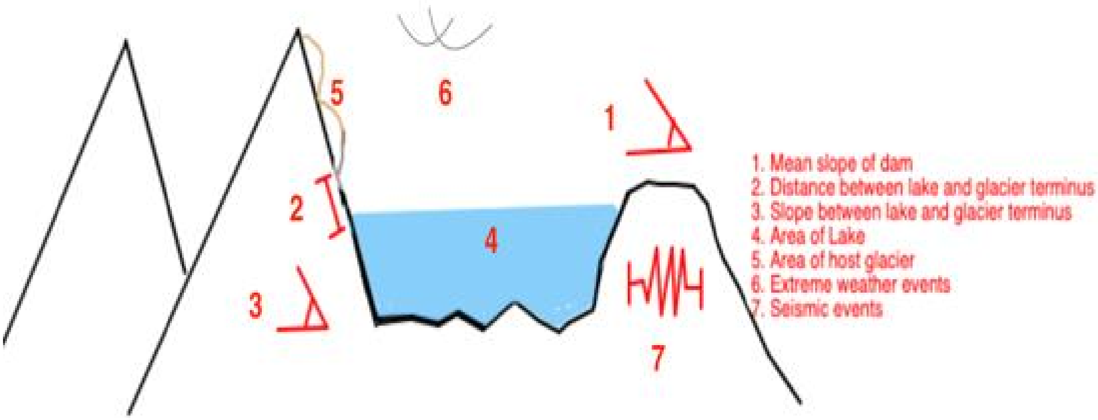

Figure 4.2 GLOF outburst triggering factor at Himalaya

The semi-automatic approach is used to map and analyse the glacier and surrounding. The unique 1D is given to each one of the glacier polygons and the glacier attribute parameters generated by combining the spatial data and digital elevation model using GIS techniques. The spectral response of glacier ice in the visible and near-infrared (NIR) bands of the electromagnetic spectrum allows the use of simple algorithms enabling semi-automatic mapping of glaciers in contrast to a time-consuming fully manual approach.

4.3.2.1 Assessing and measuring selected variables

Selected variables including mean slope of the dam (S_D), distance between lake and glacier terminus (D), slope between lake and glacier terminus (S_L), area of the lake (A_L), area of the host glacier (A_G), extreme weather (rainfall, R) and seismic events (S) were measured and modelled in various ways.

4.3.2.2 Area of the lake and host glacier

Area of the glacial lake host glacier is a very important factor to determine the vulnerability of the glacial lake. In this research these areas were delineated by using multispectral classification techniques, which exploit the maximum reflectance differences of the surface in different spectral channels to detect the anticipated object (Paul et al., 2002). Band ratioing of the near-infrared and mid-infrared bands of Landsat images in reflectance values (i.e., pixel values not converted to radiance) were used to map the glacial lake and host glacier (Paul et al., 2002). The threshold values to identify glaciers (bare ice) were defined comparing visually the band ratio image with false composite Landsat images. Normalized Difference Water Index (NDWI) of Huggel (2002) was acquired from the equation below:

$$\text{NDWI} = \frac{(Near-Infrared\ Band)-(Blue\ Band)}{(\text{Near}-\text{Infrared Band })+(\text{Blue Band})} \qquad (4.1)$$

The NDWI was applied on Landsat images. Misclassified lakes in shadowy areas and debris-covered glaciers were corrected manually. The error in lake and glacier delineation is estimated to be one pixel (i.e., ±30 m) although it can be larger in shadowy areas (Iribarren et al., 2014).

4.3.2.3 Slope and distance between host glacier terminus and glacial lake

Slope and distance between host glacier terminus and glacial lake are also important aspects of the glacial lake vulnerability assessment. This research utilizes the automatic tools (path distance) that are built in to GIS software (QGIS) to get the slope and distance between the glacial terminus and glacial lake. Series of procedure followed by Iribarren et al., (2014) has been modified. First lake outlet has been identified as the point with extreme flow accumulation in the lake from where this point the steepest descent path, 250 metres downstream (with a maximum deviation of 45°) was calculated. We assumed that moraine-dam widths are less than 300 m. At the end, the mean slope of the steepest descent path was calculated.

4.3.2.4 Seismic and rainfall data from surrounding

Seismic data set recorded since 1968 to 2018 by USSGS of the study area has been used. Certain criterion has been applied to select data set. Magnitude should be ≥4.0 on the Richter scale within 300 km radius of the area where events occurred in the Nepal Himalaya and surrounding geographic region.

Rainfall data recorded by hydrometeorology department of Nepal has been used to identify the weather vulnerability of the study area. We have analysed global temperature data extracted from NASA global weather model as well.

4.3.2.5 Digital Elevation Modelling (DEM)

This research has generated digital elevations modelling of the glacial lake and surrounding from the historical events. This will help to obtain spatial information of the lake and surrounding. The Landsat image downloaded from USGS was processed in Training Centre XML (TCX) convertor in order to obtain the elevation information of the area of interest. Then contour map was created with help of Google Earth pro map and finally process in to the QGIS to create the DEM (Fig. 4.3). The accuracy of the created DEM is ±5 m in average.

Figure 4.3 Workflow to create DEM

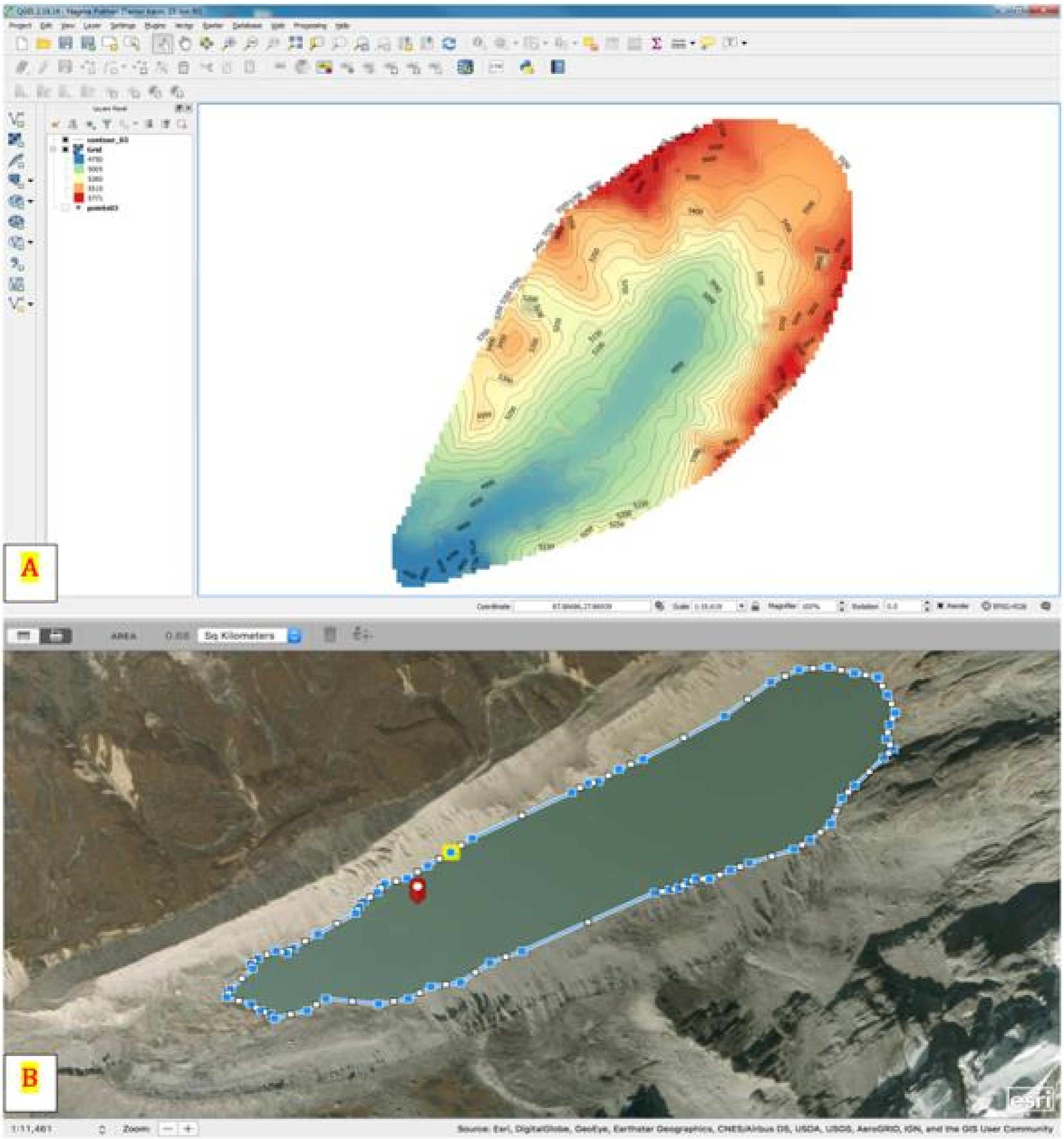

Figure 4.4 Nagma Pokhari glacial lake at Tamor basin, Nepal that suffered GLOF on 23 Jun 1980; A. DEM of the lake and surrounding, B. Area of the lake after GLOF

4.4 Results

This section summarizes the characteristics of the failed lake in historic time, looking at the cause and triggering factors that led to catastrophic failure. This analysis also helped to identify the vulnerability factors of the glacial lake and surrounding in the study area.

4.4.1 Characteristics of failed lake and past GLOFs events

Past GLOF events occurred at Nepal Himalaya within the HKH region were located in various geomorphological setting. Nine out of the eleven investigated glacial lakes that experienced GLOF in the past, were situated less than 0.75 km from the host glacier. Steep valley walls surrounded all the lakes or moraine which makes it prone to mass movements including rock-fall, snow avalanches and debris flows. These glacial lakes that experienced GLOF in the past had a dam with various geometry including steep moraine arcs and relatively flat ground moraines. Most of the failed lakes had moderate to steep outlet slopes. Some of the glacial lakes that experience GLOF events in the past are still vulnerable to the disaster including Tam Pokhari (GL_06), Nagma Pokhari (GL_03) (Table 2).

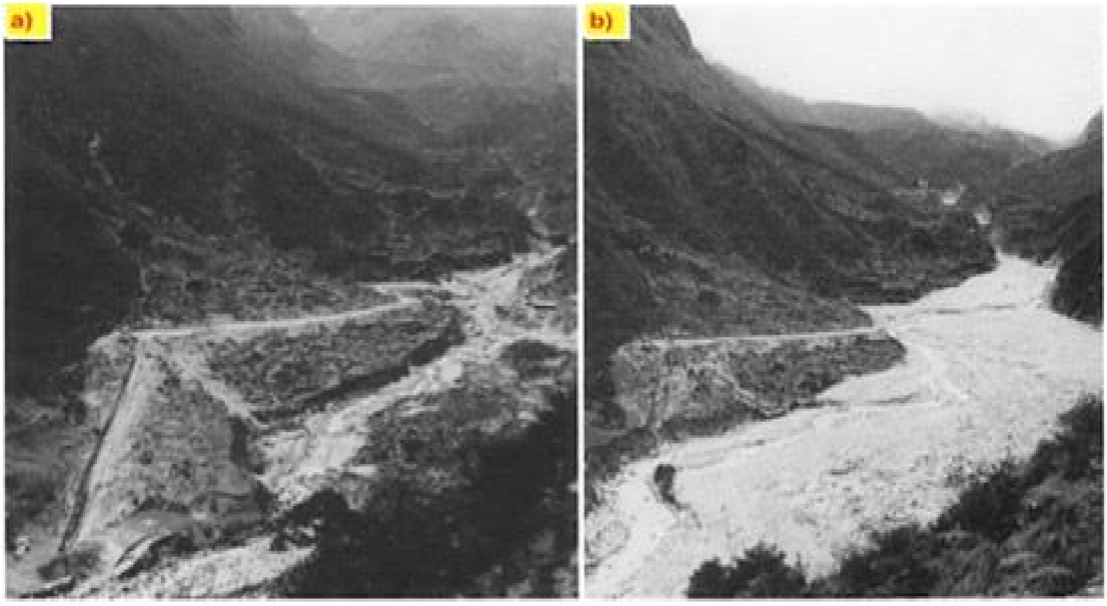

Figure 4.5 Thame Hydropower Project a) before the GLOF on 4th April 1985 and b) after the GLOF on 10th October 1985 (Vuichard, 1987)

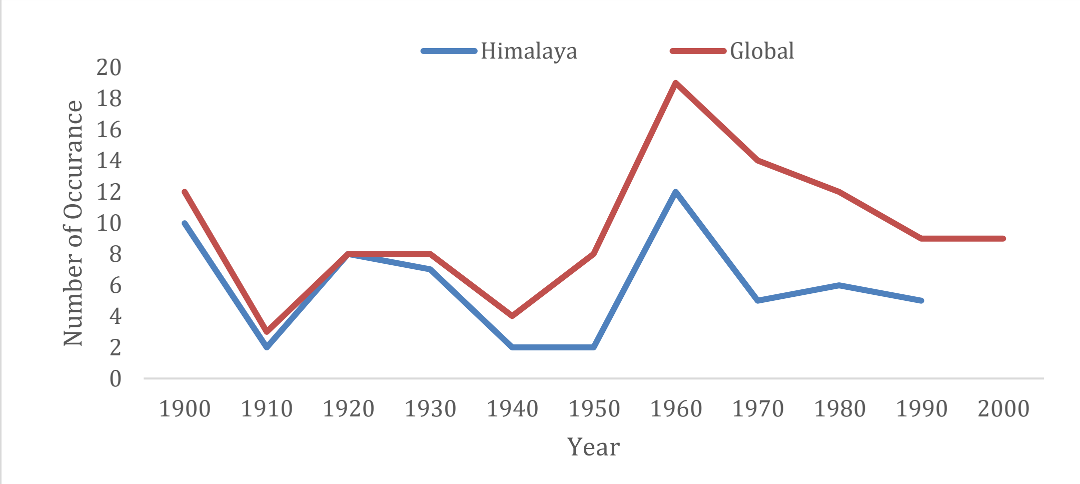

Figure 4.6 occurrence of the GLOFs since 1900 to 2000 (Osti and Egashira, 2010)

Mass movements (ice avalanche/rock fall, landslide) triggered most of these historic GLOF events at Himalaya region. This investigation concluded that, five among the eleven glacial lakes that experienced GLOF events in the past at Himalayan region do not exist anymore, while the rest suffered partial emptying which destroyed expensive high mountain infrastructure and many lives (Fig. 4.5). Tam Pokhari GLOF that occurred in 1998 released approximately 18 million m^3 of water (Osti and Egashira, 2010) with a peak discharge of about 9500 m^3/s cause extensive damage. The Dig Tsho GLOF occurred on 4^{th} August 1985 in the Dudh Koshi sub-basin with a peak discharge of 2350 m^3/s (Cenderelli and Wohl, 2001). This GLOF destroyed local villages, hydropower plant (estimated to be USD 1.5 million), about 14 bridges, and also tourism industry has been affected (Fig. 4.5). Vuichard and Zimmermann (1987) reported that the mean velocity of the front surge was about 4-5 m^3/s.

Table 4.2 Damage caused by historic GLOF events

Glacial Lake	**ID**	**Known Causes of GLOF**	**Losses (Estimated/Actual)**
Machhapuchhare, Seti Khola basin	(GL_01)	Moraine Collapse	Pokhara valley covered by 50-60m debris
Nare lake, Dudh Koshi basin	(GL_02)	Moraine Collapse	Hydropower plant
Nagma Pokhari	(GL_03)	Moraine Collapse	Villages destroyed 71 km

Tamor basin			from the origin
Dig Tsho Dudh Koshi basin	(GL_04)	Ice Avalanches	Hydropower station, 14 bridges, and others
Chubung Tsho Tama Koshi basin	(GL_05)	Moraine Collapse	Houses and farmland
Tam Pokhari Tsho Dudh Koshi Basin	(GL_06)	Ice Avalanches	Human lives and Property (NRs 156 million)
Barun Khola Arun river basin	(GL_07)	Moraine Collapse	Details not Known
Barun Khola_1 Arun river basin	(GL_08)	Moraine Collapse	Details not Known
Chokarma Cho Dudh Koshi Basin	(GL_09)	Moraine Collapse	Details not Known
Unnamed Kali Gandaki basin	(GL_10)	Moraine Collapse	Details not Known
Unnamed lake Kali Gandaki basin	(GL_11)	Moraine Collapse	Details not Known

4.4.2 Glacial Lake outburst flood triggering factors

This research investigated 11 among 30 past events recorded in the HKH region since 1930 to establish the triggering factor that led to the destructive failure which destroyed the hydropower plant and expensive mountain infrastructure by reviewing scientific literature, recorded hydro-metrological data (temperature and rainfall) and satellite Landsat imagery. Direct cause can be defined as the phenomenon that lead to instantaneous catastrophic dam failure and release of large amount of water while complex cause lead to various effects including mass movements (landslides, ice\rock avalanches), dam outlet failure, merging with adjacent glacial lakes, glacier surges, heavy precipitation, rise in temperature and so on that will result rapid expansion of outlet eventually collapsing the dam which may have devastating consequences in the flood plain downstream.

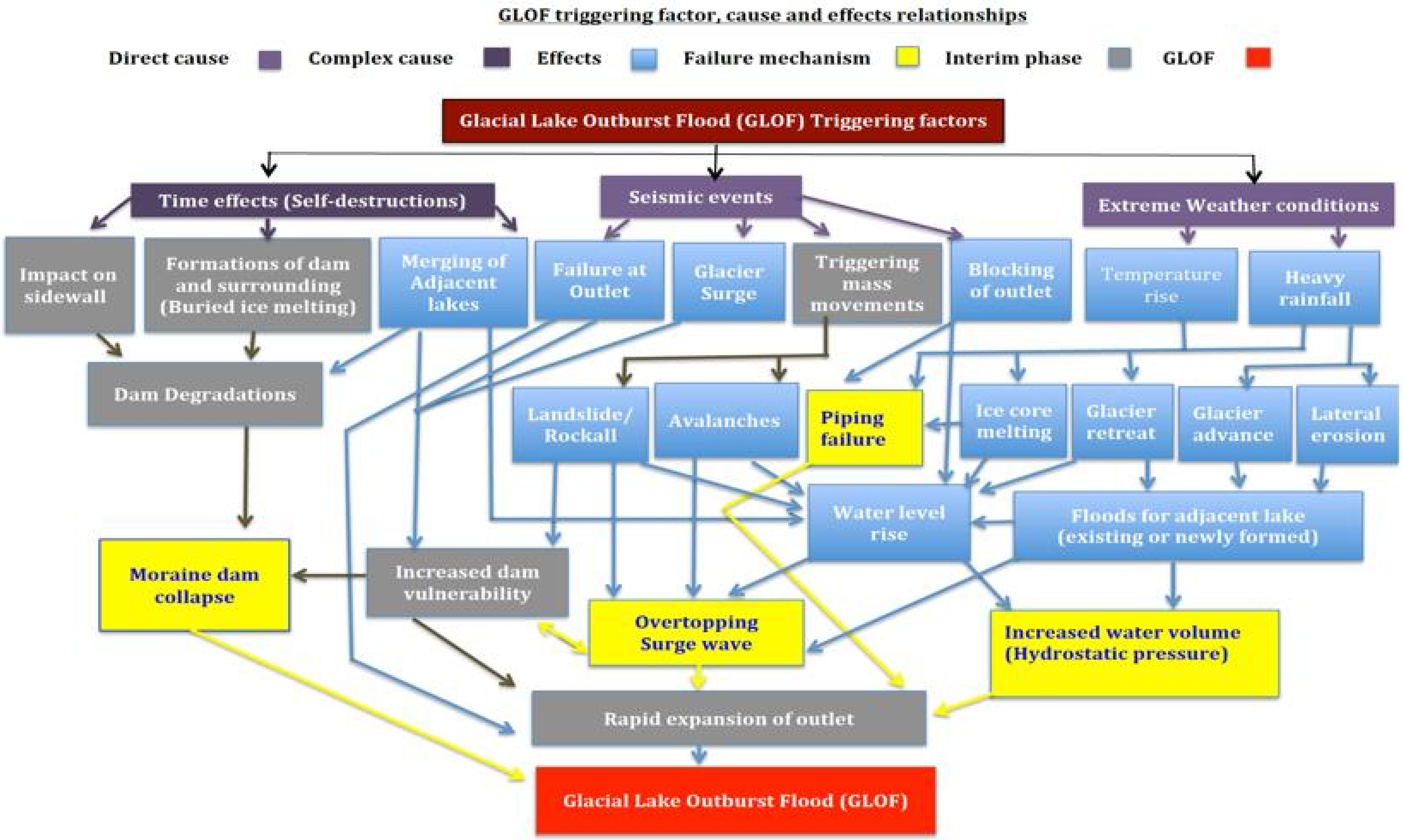

Figure 4.7

GLOF trifggring factor, cause and affect relationships

There are three main triggering factors (Fig. 4.7), of which one is considered as complex and other two as direct and these are associated with four failure mechanisms. Time-effects are the complex triggering factor that led to moraine collapse and eventually catastrophic flooding, 40% of the historical events are due to this phenomenon (Fig. 4.7). Seismic movement and extreme weather conditions are considered as the direct cause of the GLOF, which has various adverse effects to the region and led to different failure mechanisms including the increase in hydrostatic pressure on the lake, overtopping surge wave and piping or seepage failure. Hydrostatic pressure, overtopping surge wave and piping failure accounted for 23%, 13%, 7% of the recorded historical GLOF events respectively (Fig. 4.8).

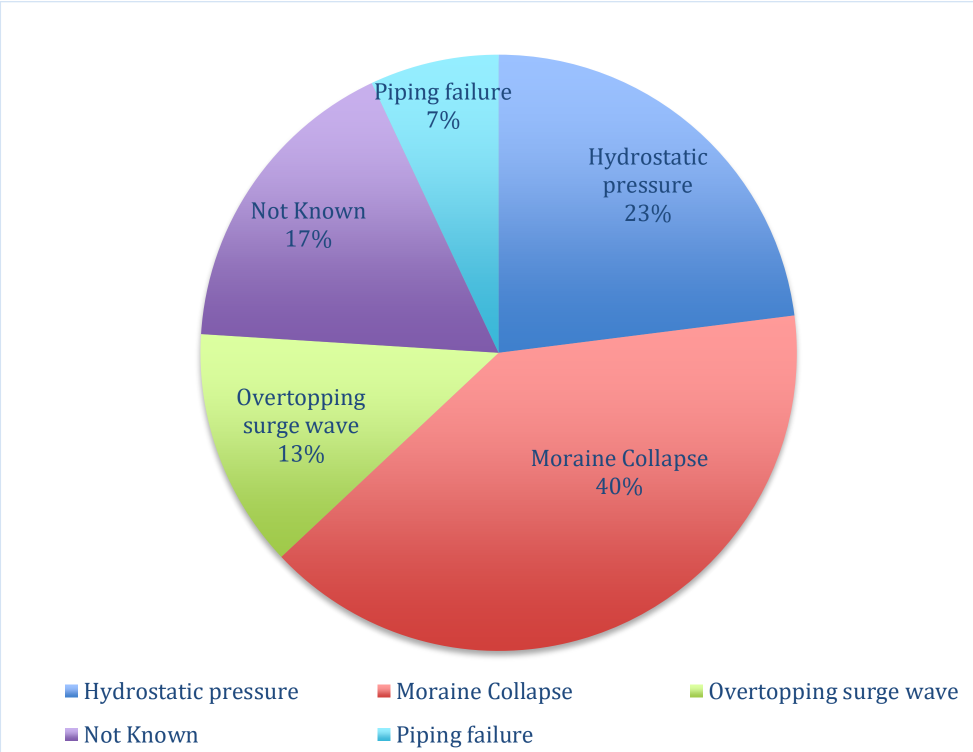

Figure 4.8 Causes of moraine-dam failure at Himalayan glacial lake based on recorded past events

4.4.3 Glacial lakes vulnerability factors at Himalayan glacial lakes

After analysing the past GLOF events, this study concluded that most of the glacial lakes that dammed by terminal and lateral-moraines, which formed during the LIA are unstable. Any other lake that are dammed by stagnant ice masses at the glacial front (Benn et al., 2012; Fujita et al., 2008) are characteristically unstable as moraine-dam parameters are subjected to frequent changes in Himalaya. Therefore, it can be concluded that most of the moraine-dammed glacial lakes are hazardous.

This research selected seven characteristics of glacial lakes: dams, their surroundings and conditioning factors that can be measured and modelled using medium-resolution satellite images, DEMs and recorded dataset. This investigation also applied few criteria to select these variables including the reproducibility of variables from each other (has to be independent variables) and factors from the historical events. Overall, these variables represent conventional outburst conditioning and triggering factors of GLOF in Himalaya region and give an idea of the damaging outburst potential of the lake. The following seven parameters of the glacier, glacial lake and surrounding have been selected based on past GLOF events in Himalaya including mean slope of the dam (S_D), distance between lake and terminus (D), slope between lake and glacier terminus (S_L), area of the lake (A_L), area of the host glacier (A_G), extreme weather (rainfall, R) and seismic events (S).

4.4.3.1 Mean Slope of the dam (S_D)

Stability of the moraine dam depends on the slope of the dam, which is denoted by S_D in this investigation. The steep outlet of the moraine dam can be more easily enlarged than low-gradient outlets if any lake discharge will occur, gradual erosion can widen and deepen the outlet leading to lake drainage. Subsequently, dams with steep outlets are more vulnerable to failure (O'Connor et al., 2001). Moreover, it has been established by Walder and O'Connor, 1997 that high dams, which produce outbursts with high peak discharges usually have steep outlets. In this investigation the average slope of the moraine dam of the glacial lake that suffered GLOF in historic time was 6.22° (Fig. 4.9) while the steepest dam slope was more than 20°.

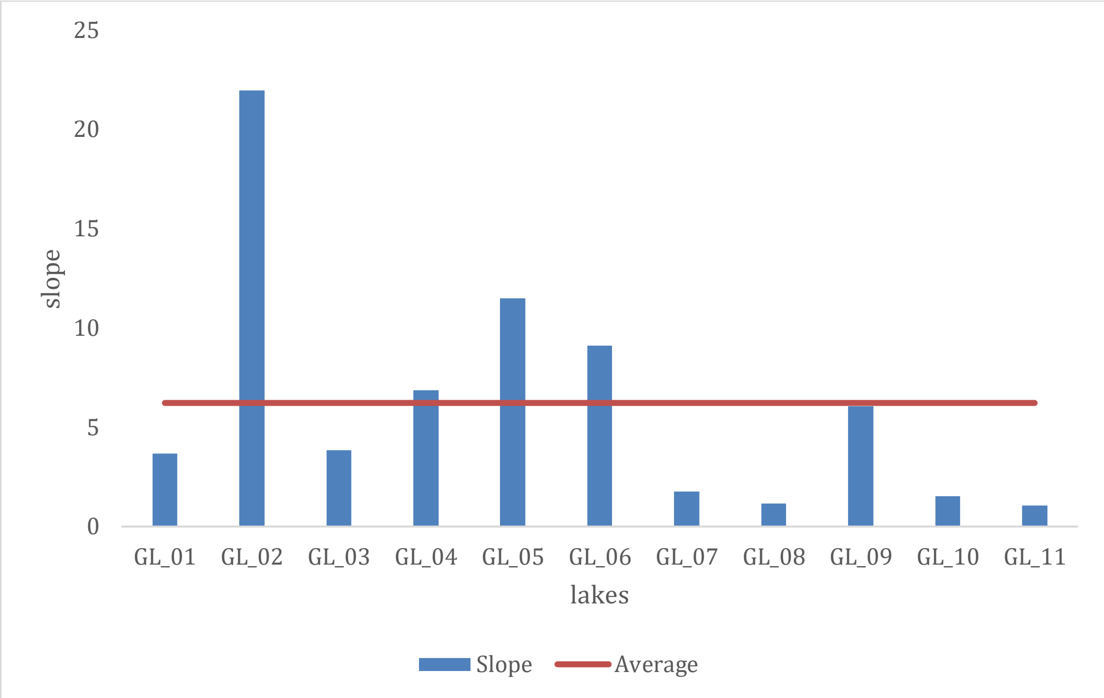

Figure 4.9 Slope of the moraine dam of the glacial lake that suffered GLOF in past at Himalaya region

4.4.3.2 Distance between glacial lake and terminus (D)

The distance between the glacial lake and glacier terminus (D) can help to determine the possibility of any mass movement (ice avalanches/rock fall) that is likely to impact the lake (Fig. 4.10). Calving and the sudden floating of dead ice from the warm glacier can affect lakes in contact or closer to the glacier. According to Richardson and Reynolds (2000a), both mechanisms can produce waves capable of overtopping dams starting a breaching process and subsequent dam failure. Icebergs can also block the lake outlet, raising the water level potentially overtopping and eventually breaching the dam. So, glacial lakes closer (or in contact) to the glaciers are considered more hazardous than lakes detached from the glacier terminus.

Here in this investigation, we have used manual digitisations method to determine the distance between the glacial lake and glacial terminus (D). According to this investigation most of the GLOF events recorded at the Himalaya region Nepal were in contact or less than ≈ 0.74 km from host glacier, which indicates that distance between the host glacier, and lake does matter.

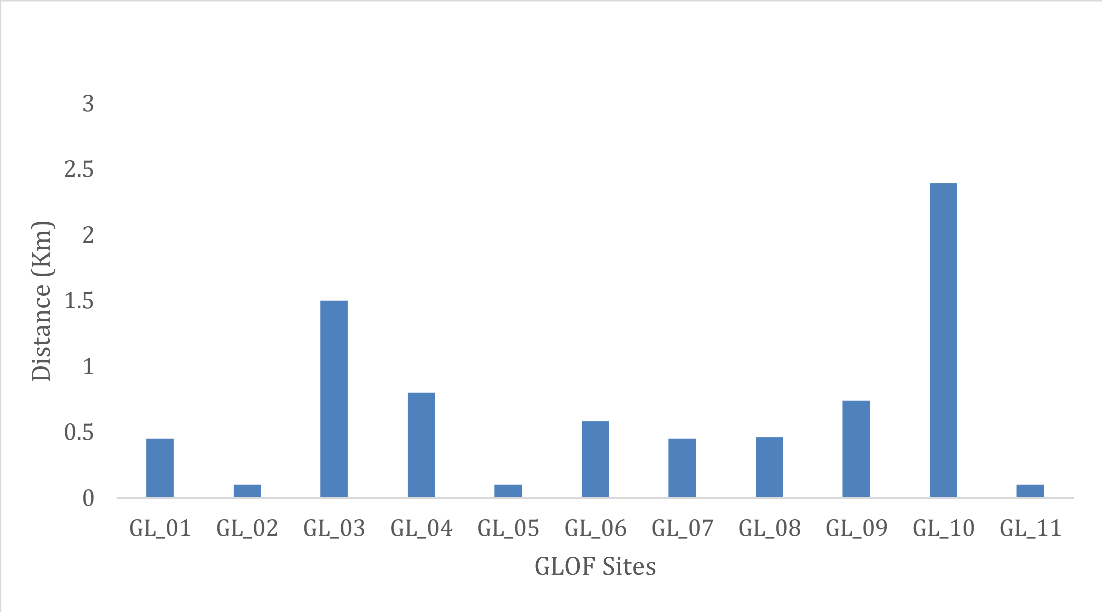

Figure 4.10 Distance between glaical lake and glacier terminus at past GLOF events

4.4.3.3 Slope between glacial lake and glacier terminus (S_L)

Slope between the glacial lake and glacier terminus can also determine the stability of the glacial lake. Steep and unvegetated slopes are a familiar source of mass movements (Peduzzi, 2010). It can promote high geomorphic activity including landslides and any mass movements. Massive and high-velocity landslides can generate impulse waves of hundreds of metres that can easily overtop dams and trigger progressive erosion and lake drainage. Large waves can also abruptly drain glacial lakes without a dam-breaching process (Clague and Evans, 2000). Impacts of the mass movements have been related to outburst floods in Himalayan glacial lakes and other regions (Harrison et al., 2006). This research found that the average slope between the glacier lake and glacier terminus was 12.25° where the past GLOF events were recorded within Nepal Himalaya.

4.4.3.4 Area of the glacial lake (A_L)

The flood damage potential, outburst volume and peak discharge are directly associated with a dimension of the lake (Costa and Schuster, 1988) as a result, colossal lakes are considered to be more hazardous than small lakes. Furthermore, according to Richardson and Reynolds (2000b), the lake with larger areas is generally more in-depth and may exert higher hydrostatic pressures over the dams making them more susceptible to failure in the Himalaya region. Moreover, large lakes also have a greater surface area potentially exposed to a mass movement and ice avalanche impacts, increasing their vulnerability toward the outburst. This research concluded that the area of the glacial lake that suffered GLOF events in the past at Himalaya varies from 0.3 km^2 to 0.7 km^2 (Fig. 4.11).

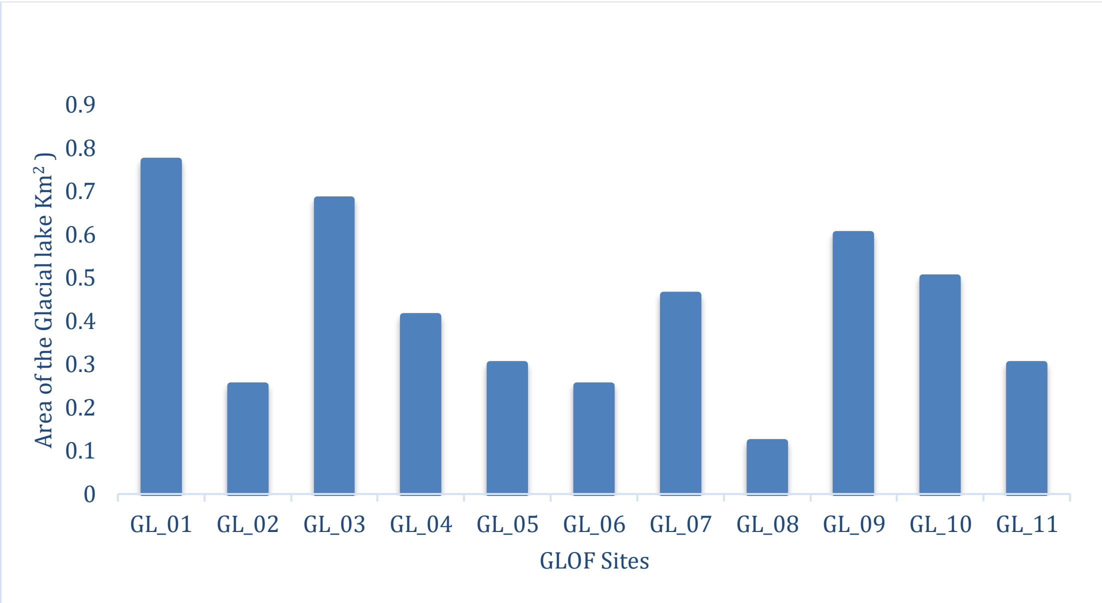

Figure 4.11 Area of the lake prior to GLOF events at Himalayan glacial lakes

4.4.3.5 Area of the host glacier (A_G)

Area of the host glacier is one of the essential components to determine the formation, expansion of the glacial lake. It reflects the area of accumulation and glacier terminus and suggests the magnitude of snow and ice avalanche if it happens. The greater the area the more it is exposed to the mass movement which subsequently will lead to GLOF events by dam failure. This research concluded that within investigated GLOF events, the maximum area of the host glacier was 4 km^2 while the smallest one was 0.2 km^2.

4.4.3.6 Weather condition; Max Temperature, Rainfall (R)

Glacier related hazards strongly depend on the local weather variations and vary in space and time. There is significant evidence that the glacier melting is strongly linked with global temperature rise. The global occurrences of the GLOF also rose

(Fig. 4.12) from 1960 to 2000 and 1960 being the most active year and the same trend was observed in Himalaya as well (Osti and Egashira, 2010). The global surface temperature sharply climbed in 1920, before it started to plunge back in 1940. The global surface temperature is an increasing trend from 1960 to date (Fig 4.12).

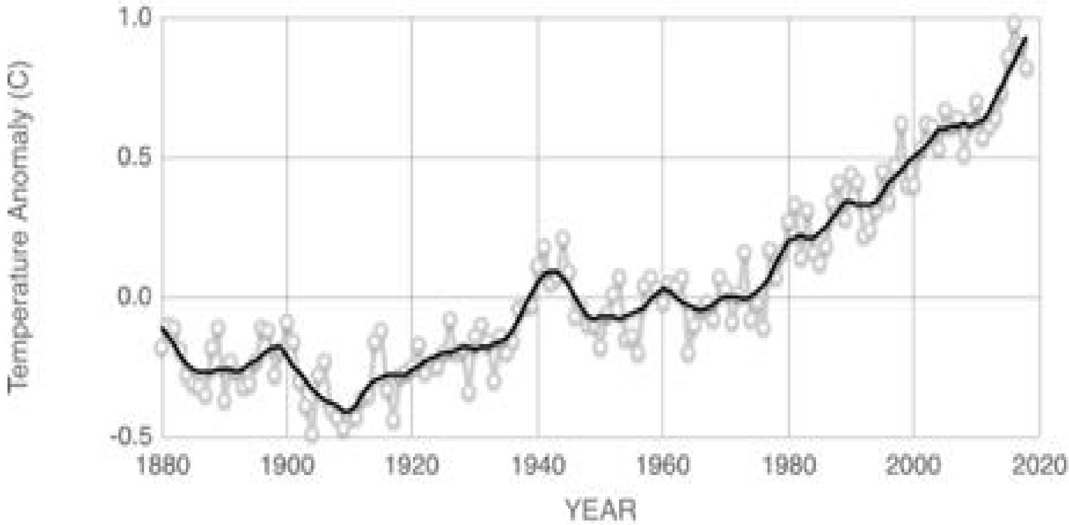

Figure 4.12 Global temperature anomalies (NASA, 2019)

Since local and regional weather condition has a significant effect on the glacier-related hazard, it is evident that torrential rainfall will weaken the dam, increasing the hydrostatic pressure on the lake, and initiate piping failure eventually leading to GLOFs. There was heavy rainfall recorded before these GLOF events occurred including the Tam Pokhari GLOF, 1998 (Osti and Egashira, 2010) in the Himalaya region. To analyse the rainfall trend 44 years rainfall data (1974-2018) recorded at Chaurikharka weather station in Mt Everest region Nepal monitored by the Department of Hydrology and Meteorology of Nepal, were studied. There are no substantial changes on peak monsoon season (July to September) but there is clearly increasing trend on July’s monthly rainfall since 2010.

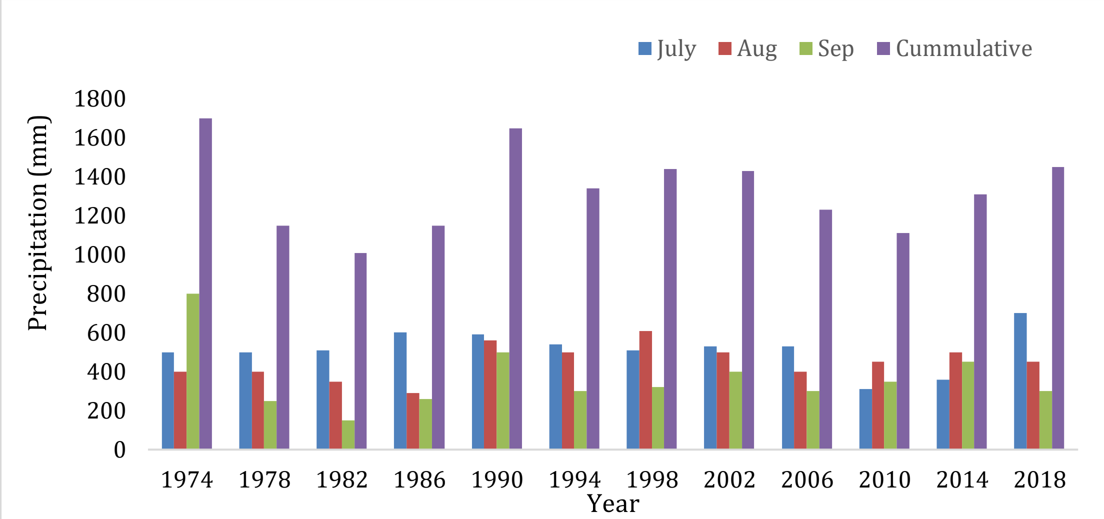

Figure 4.13 Observed precipitation at Chaurikharka Hydrological station, Nepal (Osti et al., 2011; Meteoblue, 2021)

4.4.3.7 Seismic events (S)

In the Himalaya region seismicity mainly results from the continental conflict of the India and Eurasia plates, which are converging at a relative rate of 40-50 mm/year (USGS, 2018). Northward under thrusting of India beneath Eurasia generates frequent earthquakes, which makes this area one of the most seismically hazardous regions on Earth. This research analysed recorded earthquake (>M 4.0) events within Nepal Himalaya, since 1968 to 2018 by USGS, which clearly indicates that there is clear link between the seismic activities and GLOF events (Fig. 4.13). There have been very few studies conducted to understand earthquake-triggered GLOF mechanism and limited GLOF event(s) are documented (Emmer et al., 2013). The main cause of earthquake-triggered GLOFs is dam rupture (moraine or ice dam), or earthquake-induced piping and subsequent dam failure (Lliboutry et al., 1977).

A heavy earthquake on May 1970 altered the internal structure of the dam and piping occurred from Lake Safuna Alta, Cordillera Blanca, Peru (Lliboutry et al., 1977). The lake water level decreased by approximately 38 m, by releasing a huge amount of water (4.9×10^6 m^3) retained at the time of breach. Sometimes GLOF is occurred indirectly by earthquake-triggered slope movement(s) into the lake (Strasser et al., 2003). Furthermore, it may block the natural outflow of the lake, subsequently increasing the water level, and dam failure due to the increased hydrostatic pressure or overtopping. The Gorkha earthquake in 2015 (M = 7.8 Richter scale, Nepal), showed that not every strong earthquake in the region necessarily leads to GLOF subsequently or in immediate future, it may have long-term adverse effects as well.

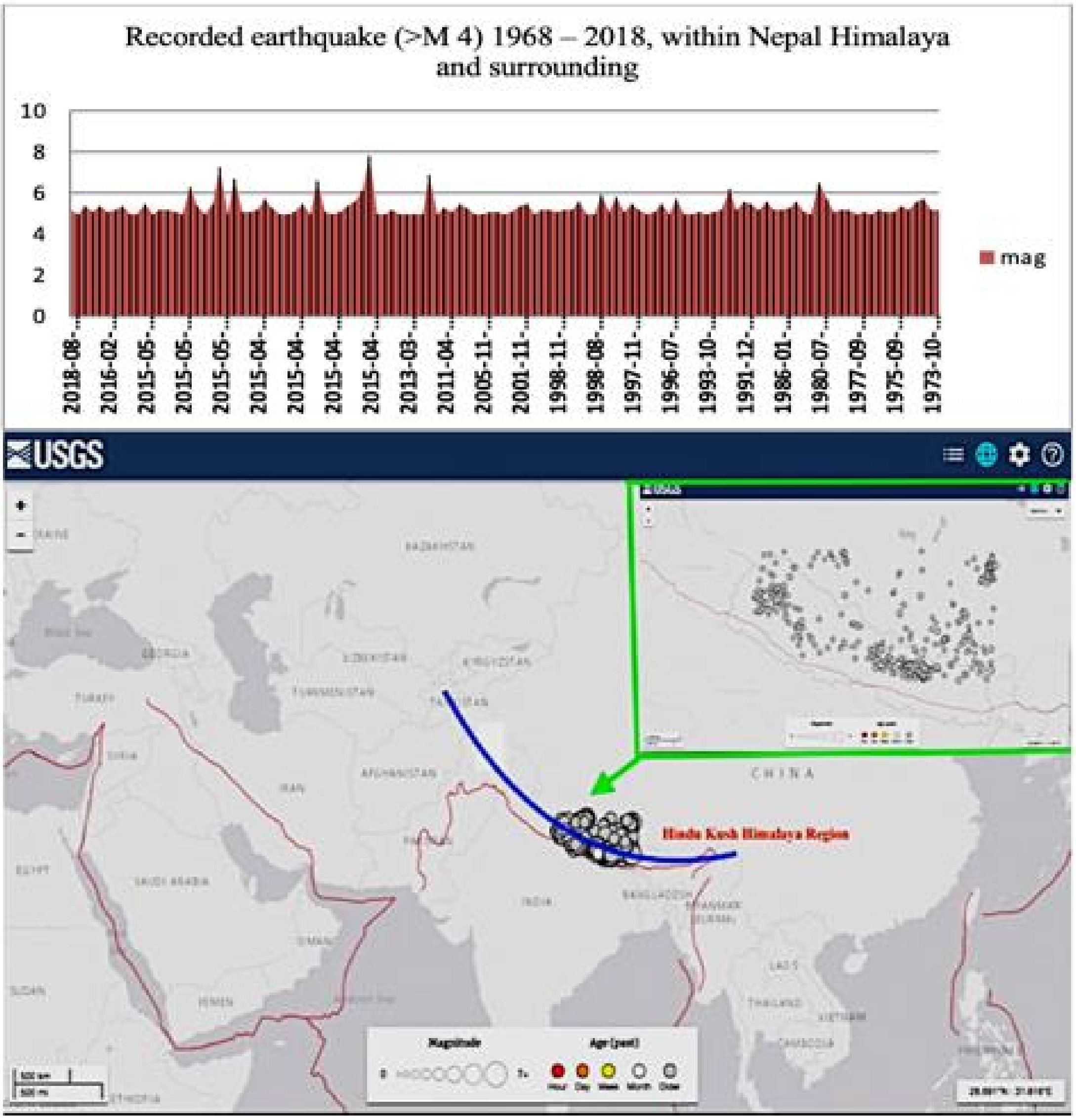

Figure 4.14 Recorded earthquake (>M 5) 1968 – 2018, within Nepal Himalaya and surrounding

4.5 Conclusion

This chapter concluded the GLOF triggering factors and conditions of the glacial lake and surrounding based on past events and suggested the seven different vulnerability parameters that can influence the stability of the glacial lake and eventually lead to catastrophic failure. By analysing these parameters, it is a relatively quick and easy way to identify the degree of danger of the glacial lake and its vulnerability. However, it is not possible to predict precisely when GLOF will occur. This will only help to provide the assessment of the glacial lake and surrounding in the study area and assist in prioritising the unstable glacial lake for further detailed assessment. Geomorphological characteristic of the glacial lake and surrounding, composition moraine dam and other extreme weather condition also affect the stability of the glacial lake. However, this is out of scope for this research to analyse these factors. The formation of the glacial hazard mainly GLOF is a dynamic process, and it is continuously evolving so continuous monitoring of glacial lake is necessary to mitigate the GLOF hazard.

This research investigated 11 GLOF events which occurred within Nepal Himalaya at the HKH region since 1930 to establish the triggering factor that led to the destructive failure by reviewing scientific literature, recorded hydro-metrological data (maximum temperature and rainfall) and satellite imagery. Based on these investigations this research also established the vulnerability factor of the glacial lake in the region. There are three main triggering factors, of which one is considered as complex and other two as direct and these are associated with four failure mechanisms. Time-effects are the complicated triggering factor that led to moraine collapse and eventually catastrophic flooding, 40% of the historical events are due to this phenomenon. Seismic movement and extreme weather conditions are considered as the direct cause of the GLOF. This has various adverse effects to the region and led to different failure mechanisms including the increase in hydrostatic pressure on the lake, overtopping surge wave and piping or seepage failure. Avalanches, glacier surge and piping failure accounted for 23%, 13% and 7% of the recorded historical GLOF events respectively.

There are seven different parameters that influenced the stability of the glacial lake in the Himalayan region including mean slope of the dam (S_D), distance between lake and glacier terminus (D), slope between lake and glacier terminus (S_L), area of the lake (A_L), area of the host glacier (A_G), extreme weather conditions (high temperature, rainfall) and seismic events (S). These vulnerability factors are chosen based on a few criteria. These data can be assessed and analysed by the medium resolution satellite imagery, topographic maps, GIS techniques and DEM and should be independent variables based on historical events.

Chapter 5

Vulnerability assessment framework of Himalayan glacial lakes, Nepal

This chapter created the unique vulnerability assessment framework of the glacial lake based on the variables and conditioning factors established in the previous chapter. The total vulnerability score (TVS) of those glacial lakes before the historic GLOF events is also calculated based on the proposed framework.

In the Himalayan region GLOF with the huge amount of debris from moraines not only causes morphological changes through the flood plain but also causes loss of life and damage to properties downstream at great distances from the sources. There have been many GLOF events experienced in Nepal with great destruction to livelihood. Global warming and subsequent melting of snow and ice, retreat of glaciers and expansion of existing glacial lakes, and emergence of new glacial lakes increase the risk of GLOF. It potentially poses huge risk to mountain communities but the loss of damage can be reduced dramatically by implementing different measures including vulnerability assessment of the glacial lake and surrounding to assess the danger to the livelihood. So, it is highly recommended that the prior assessment of GLOF before planning engineering works is necessary based on reliable data and scientific methods and observations. It is essential to assess the vulnerability of the glacial lake in order to determine the potential GLOF events in the regions and mitigate the GLOF hazard.

5.1 Introduction

Mountainous region around the world has been affected by the global warming, as a result glacial hazard has increased. They can lead to the creation and expansion of new or existing glacial lakes dammed by moraines. Particularly those moraine-dammed glacial lakes have suffered huge outbreaks in the past and at greater risks at the present. Because various factors can trigger mass movement that can affect the lake and generating impact waves and successive dam failure. The Himalayan region has repeatedly suffered disaster in the past. And there has been various hazard assessment carried out in the past but those are focused on the risk reduction, such as dam stabilizations, flood detection on dam, early warning system. However, the vulnerability assessment of the GLOF is necessary to determine potential disaster and damage that may occur.

In the Himalaya region, GLOF triggering factors and dam collapsing mechanism are complicated. Continuous monitoring of the disaster-prone area and the systemic vulnerability assessment of the glacial lake are needed to examine potential GLOF hazards. The vulnerability assessment framework has been developed by modelling the parameters that have been identified in previous chapter by the scientific method which will help us to understand the glacial hazard dynamics including GLOF that will make local communities and stockholders more resilient. The present analysis, however, does not focus on the social vulnerability of the local community and stakeholders but on assessing the probability of a lake outburst and extent of damage caused by various factors to the glacial lake and surrounding.

This study has used AHP method to determine the values of the different GLOF triggering factors along with GIS, remote sensing and expert knowledge in order to create the vulnerability assessment framework for the Himalayan glacial lake. Selected variables including mean slope of the dam (S_D), distance between lake and glacier terminus (D), slope between lake and glacier terminus (S_L), area of the lake (A_L), area of the host glacier (A_G), extreme weather (rainfall, R) and seismic events (S) were measured and modelled by above mentioned methods.

5.2 Methodology

In this research past glacial lake outburst flood has been analysed to determine the various factors that triggered glacial lake outburst in the Himalayan region, Nepal. Various criteria have been applied to select these factors with help of combined geographical information system (GIS) and DEM techniques. These selected variables of the glacial lake and surrounding has been assigned certain value depending on its contribution towards GLOF occurrence with help of AHP method. These variables further classified and critical value has been assigned based on empirical evidence. Total vulnerability score (TVS) of the glacial lake has been calculated and categorised into low (≤40%), medium (40 - 49%), high (50 - 59%) and very high (≥60%) according to the total vulnerability score (TVS) (Table 7), where likelihood of GLOF occurrence at glacial lake gradually increase from low to high TVR scoring glacial lakes.

5.2.1 Vulnerability assessment framework

In most cases the probability of the extreme flood event is calculated from its frequency or the return period of the flood (Zimmermann et al., 1997). Glacial lake outburst flood is often a unique one-off event in most cases. As glacial dynamic has been constantly changing due to the climate change and global warming so new techniques are needed to estimate the probability of glacial lake outburst flood. This research has developed the vulnerability assessment framework that can help to determine how likely the glacial lake is about to burst. This can be used as primary risk assessment tools of the glacial lakes which is often situated at remote location of the Himalaya.

Field assessment of the glacial lakes is very difficult and treacherous due to its geographical location and other several factors. The method developed by this research is based on remote sensing and GIS techniques combined with empirical evidences. The framework is mainly based on the crucial GLOF triggering factors and cause concluded by empirical evidence. So, this approach is more reliable and accurate then the pervious method as they purely rely on either statical modelling or remote sensing datasets. To validate this framework existing potential dangerous glacial lake (PDGL)'s vulnerability has been aaccessed. These tools can be used by local stakeholders, planners and developers to assess the vulnerability of the glacial lakes.

The stability of the glacial lakes depends mainly on the geomorphology of the area, characteristics of the host glaciers, characteristics of the dam and its surrounding. The materials, geometry, types of drainage and freeboard also play a vital role in dam stability (Huggel et. al., 2004). This may also affect the hydraulic gradients. Dam break can be initiated by surge wave generated by any mass movements (rock/ice avalanches) and regressive erosion. Based on these considerations the following variables have been concluded in the previous chapter: Mean Slope of the dam (S_D), Distance between lake and terminus (D), Slope between lake and glacier terminus (S_L), Area of the lake (A_L), Area of the host glacier (A_G), Extreme weather (Rainfall) (R) and Seismic events (S) has been measured and modelled to create the vulnerability assessment framework based on empirical evidences.

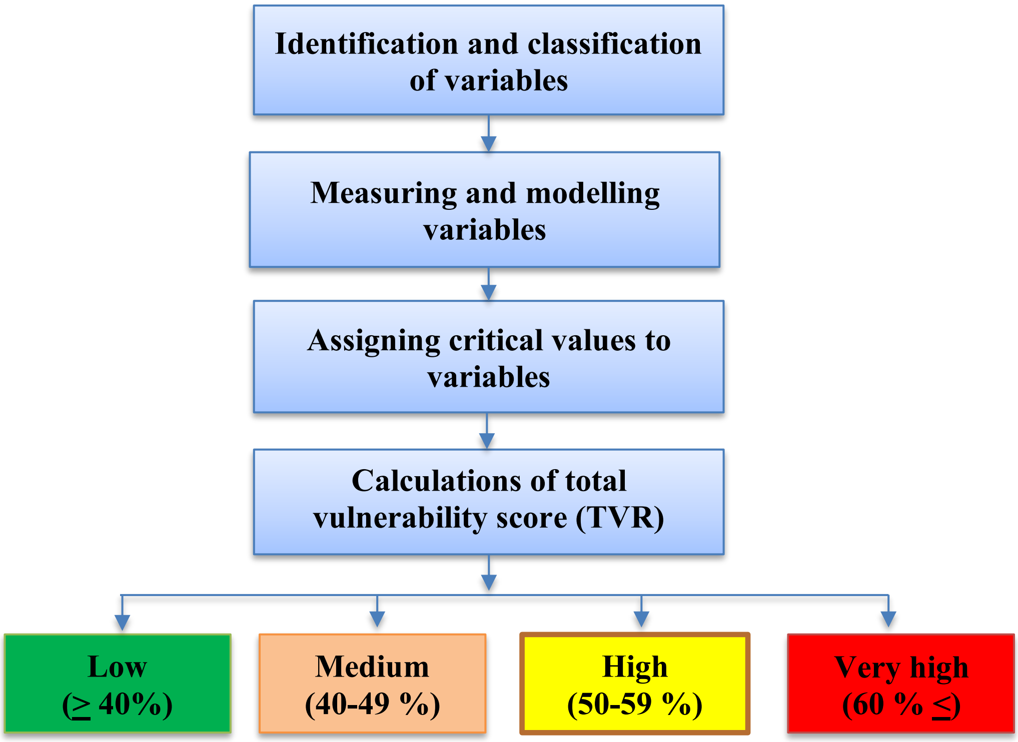

Figure 5.1 Work-flow to create Vulnerability assessment framework

5.2.2 Modelling vulnerability factor

Those selected variables or the vulnerability factors and conditions of the glacial lake has been assigned the weight based on the empirical evidence and engineering judgements with help of AHP. All variables are ranked based on their sensitivity toward GLOF. Then each variable further classified into four percentiles where each has its own values (Table. 4). The total vulnerability score (TVS) of glacial lake has been calculated by using following equation.

$$TVS = \text{Wt. of } (V_1) * \text{Class of } (V_1) + \ldots \text{Wt. of } (V_n) * \text{Class of } (V_n) \tag{5.1}$$

Where, TVS = Total Vulnerability Score, V = Variables

Maximum Total vulnerability score (TVS) of any glacial lake is one. Based on these scores the likelihood of the GLOF on these glacial lakes further divided in low, medium, high and very high based on the TVS $\leq 40\%, (41-50)\%, (51-60)\%$ and 61% respectively.

5.2.3 Analytical Hierarchy Process (AHP)

The Analytical Hierarchy (AHP) method (Saaty, 1980) is a useful method for dealing with complex decision-making process to set the priorities that involve multiple variables. This will enable the decision maker to set priorities to take any decision based on their prevalence on each other by reducing complex decisions to a series of pairwise comparisons, and then synthesising the results. The AHP helps to make both subjective and objective aspects of a decision making precess. It is also aided by techniques to check the consistency of the decision maker's evaluations, thus reducing bias in the process of decision making. The AHP considers a set of evaluation criteria, and a set of alternative options to arrive at the best decision.

In AHP, each evaluation criterion will assign specific weight according to the decision maker's pairwise comparisons of the criteria. The higher the weight, the more important the corresponding criterion. Next, for a fixed criterion, the AHP assigns a score to each option according to the decision maker's pairwise comparisons of the options based on that criterion. The higher the score, the better the performance of the option with respect to the considered criterion. Finally, the AHP combines the criteria weights and the options' scores, thus determining the overall score for each option, and a consequent ranking. The overall score for a given alternative is a weighted sum of the scores it gained with respect to all the criteria.

The AHP is a very flexible and powerful tool because the final ranking, is obtained on the basis of the pairwise relative evaluations of both the criteria and the options provided by the user. The computations made by the AHP are always guided by the decision maker's experience, and the AHP can thus be considered as a tool that is able to translate the evaluations (both qualitative and quantitative) made by the decision maker into a multi-criterion ranking. Furthermore, the AHP is a modest tool because there is no need for building a complex expert system.

The AHP method can be implemented in three simple consecutive steps:

- Computing the vector of criteria weights.
- Computing the matrix of option scores.
- Ranking the options.

Each step will be described in detail in the following. It is assumed that m evaluation criteria are considered, and n options are to be evaluated. A useful technique for checking the reliability of the results will be also introduced.

5.2.3.1 Computing the vector of criteria weights

In Analytical Hierarchy Process (AHP) the vector of the criteria of weights can be created to form matrix of the option scores. To compute the weights of the different criteria, the AHP starts creating a pairwise comparison matrix A. The matrix A is the $n \times n$ real matrix, where n is the number of evaluation criteria considered. Each entry a_{ij} of the matrix, A represents the importance of the i^{th} criterion relative to the j^{th} criterion. If $a_{ij} > 1$, then the i^{th} criterion is more important than the j^{th} criterion, while if $a_{ij} < 1$, then the i^{th} criterion is less important than the j^{th} criterion. If two criteria have the same importance, then the entry a_{ij} is 1. The entries a_{ij} and a_{ji} satisfy the following.

$$a_{ij} = a_{ji} \qquad (5.2)$$

So, $a_{ii} = 1$ for all i. The relative importance between two criteria is measured according to a numerical scale from 1 to 13, as shown in Table 1 below, where it is assumed that the i^{th} criterion is equally or more important than the j^{th} criterion. The prevalence of one over another variable on the Table below is only suggestive, and may be used to translate the decision maker's qualitative evaluations of the relative importance between two criteria into numbers. It is also possible to allocate intermediate values, which do not correspond to a precise interpretation. The matrix "A" is created by pairwise comparison of variable in consistent manner.

Table 5.1 Value and interpretation of variables

Value of a_{ij}	Interpretation
1	i and j are equally important
3	i is slightly important than j
5	i is slightly more important than j
7	i is more important than j
9	i is strongly more important than j
11	i is absolutely more important than j
13	i is extremely more important than j

5.2.3.2 Pairwise comparison matrix (A)

The following pairwise comparison matrix has been created based on importance of the selected variables of the glacial lakes and surrounding. Where Mean Slope of the dam (S_D), Distance between lake and terminus (D), Slope between lake and glacier terminus (S_L), Area of the lake (A_L), Area of the host glacier (A_G), Extreme weather (Rainfall) (R) and Seismic events (S) has been categories according on their prevalence to one another based on historical facts and expert engineering judgements.

Table 5.2 Pairwise comparison matrix (A)

			Pairwise comparison matrix (A)				
	S_D	D	S_L	A_L	A_G	R	S
S_D	1	3	5	7	9	11	13
D	0.33	1	5	7	9	11	13
S_L	0.2	0.2	1	7	9	11	13
A_L	0.14	0.14	0.14	1	9	11	13
A_G	0.11	0.11	0.11	0.111	1	11	13
R	0.09	0.09	0.09	0.091	0.091	1	13
S	0.08	0.08	0.08	0.077	0.077	0.077	1
Sum	1.96	4.62	11.4	22.28	37.17	56.08	79

5.2.3.3 Normalize pairwise matrix (A_{normal})

In Analytical Hierarchy Process (AHP) once the matrix A is created, it is possible to derive from A the normalized pairwise comparison matrix A_{normal} by making equal to 1 the sum of the entries on each column, i.e., each entry $\overline{a_{ij}}$ of the matrix A_{normal} is computed as follow.

$$\overline{a_{ij}} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \tag{5.3}$$

Table 5.3 Normalize matrix (A_{normal})

	Normalize matrix (A_{normal})							
	S_D	**D**	**S_L**	**A_L**	**A_G**	**R**	**S**	**Av.Row/Weight**
S_D	0.512	0.649	0.438	0.314	0.242	0.196	0.165	0.359
D	0.17	0.216	0.438	0.314	0.242	0.196	0.165	0.249
S_L	0.102	0.043	0.088	0.314	0.242	0.196	0.165	0.164
A_L	0.073	0.031	0.013	0.045	0.242	0.196	0.165	0.109
A_G	0.057	0.024	0.01	0.005	0.027	0.196	0.165	0.069
R	0.047	0.02	0.008	0.004	0.002	0.018	0.165	0.038
S	0.039	0.017	0.007	0.003	0.002	0.001	0.013	0.012
Sum	1	1	1	1	1	1	1	1

5.2.3.4 Criteria weight vector (w)

Finally, in Analytical Hierarchy Process (AHP) the criteria weight vector w (that is an n-dimensional column vector) is built by averaging the entries on each row of A_{normal} matrix, i.e., average row of the normalize matrix is the weight of the individual variables of the matrix.

$$w_i = \frac{\sum_{l=1}^{m} \bar{a}_{jl}}{n} \tag{5.4}$$

Table 5.4 Weight of the variables

Weight of variable (av. of row from normalize matrix)		
Ranging	**Variables**	**Weight**
1st	S_D	0.359
2nd	D	0.249
3rd	S_L	0.164
4th	A_L	0.109
5th	A_G	0.069
6th	R	0.038
7th	S	0.012

5.2.3.5 Classifications and critical values of the variables

In AHP method this is very important and concluding steps towards calculating total vulnerability score (TVS) of any glacial lake based on past events.

In this phase critical values of the all-selected variables have been assigned based on the empirical evidence and past events from around the different parts of the world. All these selected variables including Mean Slope of the dam (S_D), Distance between lake and terminus (D), Slope between lake and glacier terminus (S_L), Area of the lake (A_L), Area of the host glacier (A_G) are further divided into four different percentiles from 0.25 to 1 based on their values while Extreme weather (Rainfall) (R) and Seismic events (S) are only scoring 0/1 based on their occurrences during the particular events.

5.2.4 Total vulnerability score (TVS) calculation

To conclude the vulnerability assessment of the glacial lake, the lake's total vulnerability score (TVS) can be calculated. The maximum possible total vulnerability score of any glacial lake is 1. Total vulnerability score (TVS) of the glacial lake can be calculated by following.

TVS = Wt. of variables (V_1) x class of variable (V_1) + … wt. of variables (V_n) x class of variable (V_n) (5.5)

Once TVS is calculated, the likeliness of the GLOF occurrence can be further divided into low, medium, high and very high categories based on their total vulnerability of score. This will help to prioritise the resources to effective GLOF hazard mitigation planning

Table 5.5 Weight, classifications and critical values of the variables and conditioning factors

Variables and its weights						
Mean Slope of the dam	**Distance between lake and terminus**	**Slope between lake and glacier terminus**	**Area of the lake**	**Area of the host glacier**	**Extreme weather (Rainfall)**	**Seismological events**
(S_D), (^{0})	**(D), (km)**	**(S_L), (^{0})**	**(A_L), (Sq. km)**	**(A_G), (Sq. km)**	**(R), (mm)**	**(S), (Mw)**
0.359	0.249	0.164	0.109	0.069	0.038	0.012
Note: weighting of these variables has been assigned criteria weighting vector						
Classifications of variables and critical values						
$S_D \leq 5^0 = 0.25$	D > 0.90 = 0.25	$S_L < 7^0 = 0.25$	$A_L = 0.01 - 0.1 = 0.25$	$A_G < 0.5 = 0.25$	Yes - 1	Yes - 1
SD = (60 -100) = 0.5	D = (0.301 - 0.9) = 0.5	$S_L = (8^0 - 12^0) = 0.5$	$A_L = 0.1 - 0.5 = 0.5$	$A_G < (0.5 - 1) = 0.5$	No - 0	No - 0
$S_D = (11^0 - 14^0) = 0.75$	D = (0.09 - 0.30) = 0.75	$S_L = (13^0 - 16^0) = 0.75$	$A_L = 0.5 - 0.8 = 0.75$	$A_G < (1 - 1.5) = 0.75$	Recorded events	Recorded events
$S_D > 15^0 = 1$	$D \leq 0.08 = 1$	$S_L > 16^0 = 1$	$A_L > 0.8 = 1$	$A_G > 1.5 = 1$	> 300 mm	> 4.0 Mw
(Modified from Iribarren et al., 2014)	(Based on historic GLOF events; Wang et al., 2011)	(Modified from Emmer and Vilímek, 2013; Wang et al., 2011)	(Modified from Iribarren et al., 2014; Geomorphological analysis of the area based on remote sensing)	(Based on historic GLOF events; Geomorphological analysis of the area based on remote sensing)	(Based on past GLOF events; Recorded rainfall in the area)	(Based on historic GLOF events; Recorded seismic event (> 4.0 Mw) in the region; Data acquired from USGS, 2018)

5.3 Results

This chapter has conducted vulnerability assessment of the eleven glacial lakes that suffered historic GLOF events in the past using proposed vulnerability assessment framework. Six glacial lakes had vulnerability scored very high, four glacial lakes scored medium and one glacial lake scored low. These results show that all lakes were very vulnerable to the GLOF prior to the burst.

5.3.1 Calculations of total vulnerability score (TVS)

To conclude the vulnerability assessment of the glacial lake, total vulnerability of score of the glacial lake prior to the GLOF has been calculated. Maximum possible total vulnerability score of any glacial lake is 1. Among these investigated glacial lakes, the maximum TVS of the glacial lake is 0.881 while lowest value is 0.404 prior to GLOF. Total vulnerability score (TVS) of the glacial lake can be calculated by following.

TVS = Wt. of variables (V_1) x class of variable (V_1) + … wt. of variables (V_n) x class of variable (V_n) (5.6)

Table 5.6 Calculations of total vulnerability score of glacial lake prior to historic GLOF events

Varibles →	**Sd**	**Class**	**Score**	**D**	**Class**	**Score**	**Sl**	**Class**	**Score**	**Al**	**Class**	**Score**	**Ag**	**Class**	**Score**	**R**	**Class**	**Score**	**S**	**Class**	**Score**	**TVS**	**Remarks**
Varaibles weight →	**0.36**			**0.25**			**0.16**			**0.11**			**0.07**			**0.04**			**0.01**			**1**	
Glacial lake (past GLOF events) ↓																							
1. Machhapuchhare, Seti Khola basin*0,(GL_01)	3.66	0.25	0.09	0.45	0.5	0.12	3.65	0.25	0.04	0.77	0.75	0.08	0.5	0.25	0.02	0.04	1	0.04	0.01	1	0.01	0.404	medium
2. Nare lake, Dudh Koshi basin*0, (GL_02	22	1	0.36	0.1	1	0.25	9.64	1	0.16	0.25	0.5	0.05	0.12	0.25	0.02	0.04	1	0.04	0.01	1	0.01	0.882	very high
3. Nagma Pokhari, Tamor basin *,(GL_03)	3.85	0.25	0.09	1.5	0.75	0.19	18.2	1	0.16	0.68	0.75	0.08	4.5	1	0.07	0.04	1	0.04	0.01	1	0.01	0.629	very high
4. Dig Tsho, Dudh Koshi basin X, (GL_04)	6.85	0.25	0.09	0.8	0.25	0.06	25.3	1	0.16	0.41	0.5	0.05	0.7	0.5	0.03	0.04	1	0.04	0.01	1	0.01	0.443	medium
5. Chubung Tsho, Tama Koshi basin 0 X, (GL_05)	11.5	0.75	0.27	0.1	1	0.25	3.15	0.25	0.04	0.3	0.5	0.05	4	1	0.07	0.04	1	0.04	0.01	1	0.01	0.721	very high
6. Tam Pokhari Tsho, Dudh Koshi Basin X, (GL_0	9.1	0.5	0.18	0.58	0.5	0.12	22.4	1	0.16	0.25	0.5	0.05	2.85	1	0.07	0.04	1	0.04	0.01	1	0.01	0.63	very high
7. Barun Khola, Arun river basin *, (GL_07)	1.76	0.25	0.09	0.45	0.5	0.12	22.2	1	0.16	0.46	0.5	0.05	3.65	1	0.07	0.04	1	0.04	0.01	1	0.01	0.54	High
8. Barun Khola, Arun river basin *,(GL_08)	1.16	0.25	0.09	0.46	0.5	0.12	12.4	0.75	0.12	0.12	0.5	0.05	0.65	0.5	0.03	0.04	1	0.04	0.01	1	0.01	0.464	medium
9. Chokarma Cho Dudh Koshi Basin*0,(GL_09)	6.04	0.75	0.27	0.74	0.25	0.06	6.89	0.25	0.04	0.6	0.08	0.01	0.2	0.25	0.02	0.04	1	0.04	0.01	1	0.01	0.436	medium
10. Unnamed, Kali Gandaki basin, (GL_10)	1.51	0.25	0.09	2.39	0.25	0.06	0.37	0.25	0.04	0.5	0.5	0.05	1.55	1	0.07	0.04	1	0.04	0.01	1	0.01	0.355	low
11. Unnamed lake, Kali Gandaki basin0,(GL_11)	1.05	0.25	0.09	0.1	1	0.25	10.6	0.5	0.08	0.3	0.75	0.08	3.6	1	0.07	0.04	1	0.04	0.01	1	0.01	0.61	very high

5.3.2 Vulnerability classification of the glacial lake

To get further understanding and assess the GLOF hazard posed by these glacial lakes, they are classified into four different categories based on the total vulnerability score (TVS) of the glacial lakes. The likeliness of the GLOF occurrence at these glacial lakes are divided in to low, medium, high and very high based on total vulnerability score (Table 7). The priorities should be given to them accordingly, in order to assess the GLOF hazards. Any glacial lake that scored total vulnerability score (TVS) 'Very high' should be given immediate attention and further field investigation should be carried out to mitigate the potential hazard and identify the risks. While 'medium' and 'low' categorised glacial lakes can be continuously monitored and appropriate action should be taken. Because even though 'low' risk classified glacial lake may suffer catastrophic dam failure as there are various external factors which can trigger dam failure.

Table 5.7 Vulnerability classifications

Total vulnerability score (TVS)	**Vulnerability classifications**
TVS < 40%	Low
TVS = (41- 50) %	Medium
TVS = (51-60) %	High
TVS > 61%	Very high

Among those investigated eleven GLOF events and relevant glacial lakes, six were classified as very high, four classifieds as medium and one of the glacial lakes was classified as low risk of GLOF according to their condition prior to the catastrophic dam failure. This concludes that all the glacial lakes were highly vulnerable to the GLOF except one glacial lake based on the proposed vulnerability assessment framework (Fig. 5.2).

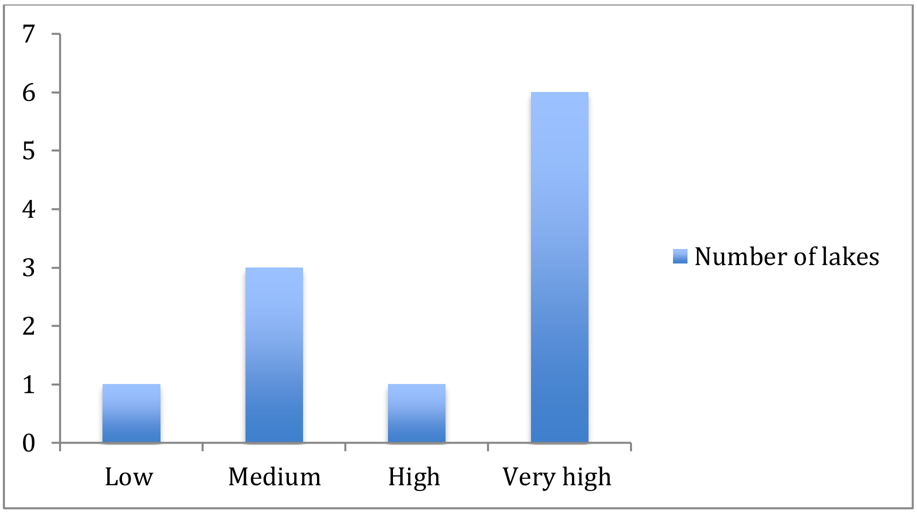

Figure 5.1 Vulnerability of the lakes prior to the historic GLOF event

5.4 Validation of the vulnerability assessment framework

This study conducted the vulnerability assessment of the historic glacial lakes before they suffered catastrophic GLOF events using the proposed vulnerability assessment framework. It concluded the vulnerability of a total of 11 glacial lakes, most of which scored very high and high TVS, hence they were likely to suffer GLOF events. Therefore, this retrospective measuring and modelling of the glacial lakes prove this proposed vulnerability assessment framework's reliability.

To further validate the proposed vulnerability assessment tools, this research has examined the vulnerability of the existing vulnerable lake (likely to burst), which has been studied and established by various scientific research conducted by the International Centre for Integrated Mountain Development (ICIMOD, 2011). ICIMOD is a regional intergovernmental body currently serving eight members within the Hindu Kush Himalayas region for knowledge sharing. Also, the government authorities in Nepal have identified those PDGL. Currently, there are 21 glacial lakes within Nepal that have been classified as PDGL by the authorities. But this is not an exclusive list as geomorphology changes over the time and there are other various factors that influence the lake's stability.

This research has conducted the vulnerability assessment of those 21 PDGL by aforementioned methodology and assessment framework and it presented in following chapters.

5.5 Conclusion

From the detailed investigation of the past GLOF events on the previous chapter, this chapter further identified, measured and modelled the glacial lake vulnerability factor including Mean Slope of the dam (S_D), Distance between lake and terminus (D), Slope between lake and glacier terminus (S_L), Area of the lake (A_L), Area of the host glacier (A_G), Extreme weather (Rainfall) (R) and Seismic events (S) based on combined AHP, QGIS and empirical evidence. By analyzing these factors, the total vulnerability score (TVS) of the lake has been calculated.

These factors, have been categorized based on each other's prevalence and assigned their weight according to their importance based on the AHP method. The values of these factors further divided into four different percentiles, and the total score of the factor is calculated. The TVS of any glacial lake can be calculated by adding the total score of all the factors. Maximum possible TVS of any lake can be 1(100%). To improve the reliability of the proposed vulnerability assessment framework, TVS further divided into four different categories based on their likeliness of suffering GLOF (Table 7). They are Low, Medium, High and Very High. Based on this proposed vulnerability assessment framework, the vulnerability of 11 glacial lakes before the GLOF events was examined. Furthermore, within those investigated glacial lakes, the vulnerability of six of them was categorized as very high, four of them are medium, and one categorized as low.

To validate the effectiveness of this proposed vulnerability assessment framework. This research has conducted the vulnerability assessment of the historic glacial lakes. The results concluded that most of the glacial lake had very high and high vulnerability score which indicates they were prone to disaster. Hence, this suggests that the effectiveness of the proposed vulnerability assessment framework is very high. This will save time and resources to categorizes the vulnerability of the glacial lake for further field investigation and close monitoring. Often the field investigation of these glacial lakes is very labor intensive and challenging due to its remoteness of the locations and small window period around the year to assess the site due to weather.

Chapter 6

Integrated approach to GLOF hazard mitigation and climate change adaptations.

The previous chapter concluded the GLOF vulnerability assessment framework of the glacial lake. This will help to assess how likely the glacial lake will suffer the GLOF. This is vital in order to draw contingency plan and mitigate the hazard in long-term. Along with continuous monitoring and assessing the GLOF related hazard it is also vital to focus on how to manage the disaster risk and adapt the changing climate to make a more resilient community. So, this chapter will explore disaster risk management and climate change adaptation by analysing the historical events. Also, GLOF hazard management strategy and various lake-lowering project that has been carried out in the past in HKH region in Nepal has been studied.

This chapter further examines the effectiveness of this proposed vulnerability assessment framework and disseminate the finding that this research has conducted on the vulnerability assessment of the existing PDGL established by various scientific studies. There are currently about 21 PDGL in Nepal. Furthermore, through the case studies this chapter investigates the Imja lake lowering project, Tsho Rolpa lake channel construction project, early warning system and monitoring. These case studies have examined different variables to identify the positive and negative socio-environmental factors towards disaster risk reduction and climate change adaptation. This will help to take holistic approach towards integrated disaster risk reduction and climate change adaptation where the proposed vulnerability assessment framework can contribute significantly.

6.1 Introduction

Since post-little Ice Age glacier has been retreating trough out the world, which is resulting in different natural disaster and risks including glacial lake outburst flood. High mountain regions around the world have been constantly in risk of the GLOF since then. Due to various socio-economic reasons this community is greatly exposed to the constantly evolving risk caused by climate change. The GLOF has capacity to mobilize a large amount of sediment and debris form moraine dam and surrounding.

This effect of the GLOF is very difficult to predict. It may have devastating effect to the downstream communities and their livelihood. Hence, holistic GLOF risk reduction measure should be taken.

There is no such thing as a "natural' disaster, only natural hazard because disaster is political and socio-economical that involves people (McNicoll et al., 1996). The GLOF disaster can be reduced by three elements: (1) by reducing the likelihood of the events; (2) by reducing the exposure; and (3) by improving community resilience (preparedness). This can be achieved by various hardcore engineering and soft solution by taking a bottom-up approach with the help of the local community. This is particularly important in the mountainous region of the world, which is vulnerable to the extreme climate events. The IPCC (2019), suggested that warming temperature led to the reduction of snow and ice masses and formation of the moraine-dammed glacial lake with high potential of destructive GLOFs, ice and rock avalanches and other glacier related hazard such as glacier-related hazards such as deterioration of steep glaciers and rock slopes (IPCC, 2019).

6.2 Vulnerability Assessment of existing PDGL

There are various studies (ICIMOD, 2011; Khadka, Zhang and Chen, 2019) conducted to investigate the status of the glacial lakes in Nepal and Himalayan region. According to ICIMOD there are about 21 PDGL with in the Nepal which is likely to suffer GLOF at any time. They have used combinations of the remote sensing and extensive field study to identify these lakes. Continuous monitoring of these glacial lakes and surrounding is necessary to reduce the risks and potential harm to downstream community and stakeholders. The past GLOF events in Nepal and transboundary has been very damaging and that has destroyed many infrastructures and human settlement as well as loss of biodiversity. This study has conducted vulnerability assessment of those PDGL by using the proposed assessment framework and concluded that seven of these glacial lakes have vulnerability score very high, four lakes scored high, five lakes scored medium and rest of the lake's TVS was low.

Table 6.1 PDGL and their vulnerability score (TVS)

Potential Dangerous Glacial Lakes (PDGL)	Total vulnerability score (TVS)
1. Tsho Rolpa [GL Code: kotak_gl_0009]	0.63525
2. Lower Barun [GL Code: koaru_gl_0009]	0.614
3. Imja Cho [GL Code: kodud_gl_0184]	0.6975
4. Lumding Cho [GL Code: kodud_gl_0036]	0.60775
5. Chamlang Cho [GL Code: kodud_gl_0242]	0.85875
6. Thulagi (Dona) [GL Code: gamar_gl_0018] [D1]	0.60775
7. Nagama Pokhari [D2] [GL Code: kotam_gl_0135]	0.579
8. Hongu2 [GL Code: kodud_gl_0241] [D2]	0.75875
9. Tam Pokhari [GL Code: kodud_gl_0193] [D2]	0.59425
10. Hongu1 [GL Code: kodud_gl_0229] [D2]	0.5185
11. [GL Code: kotam_gl_0193]	0.50715
12. [GL Code: Gakal_gl_0004]	0.59425
13. Barun Pokhari [GL Code: koaru_gl_0012]	0.491
14. East Hongu 1 [GL Code: kodud_gl_0238]	0.36895
15. [GL Code: Gabud_gl_0009]	0.4895
16. Mera [GL Code: kodud_gl_0220]	0.38025
17. [GL Code: koaru_gl_0016]	0.47035
18. [GL Code: Gakal_gl_0008]	0.33925
19. [GL Code: kotam_gl_0111] (lahare taal)	0.47275
20. East Hongu 2 [GL Code: kodud_gl_0239]	0.39075
21. Kaligandaki [GL Code: gakal_gl_0022]	0.39375

6.2.2 Vulnerability classification of potentially dangerous glacial lake (PDGL)

These glacial lakes categorised as PDGL need continuous monitoring to minimise the GLOF related hazard to downstream community and floodplains. Based on expansion rates, glacier, dam and surrounding conditions, topographic characteristics these lakes are further divided into three different categories including Low (D1), medium (D2) and high (D3) by ICIMOD (2011). Among them Tsho Rolpa is the biggest glacial lake with area of 1.75 km^2 which has suffered GLOF in the past. The Imja Tsho (lake) is one of the dangerous glacial lakes where separate channel was constructed in 2016 by Nepalese authorities to reduce the water level.

According to ICIMOD among 21 PDGL six glacial lakes were classified as highly dangerous including Imja Tsho, Tsho Rolpa, Thulagi, Chamlang South, Lumding Tsho, and Lower Barun Tsho. This study also found all these six lakes are highly critical including Hongu2 glacial lake. Both studies categorised same number of the glacial lake with medium risks while rest of the lakes were identified as low risk by ICIMOD. However, this study further divided them into medium and low risk categories.

Hence, the proposed tools are quite accurate to assess the vulnerability of the glacial lake.

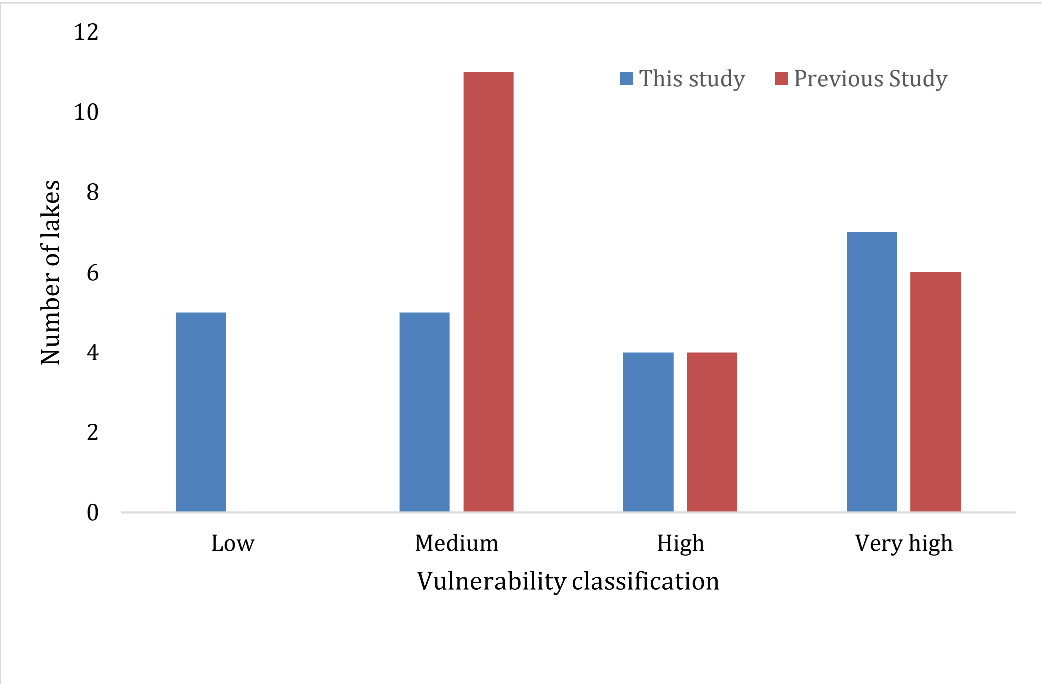

Figure 6.1 Vulnerability classification of PDGL

Table 6. 2 Vulnerability assessment of the 21 PDG

Vulnerability assessment of the existing Potentially Dangerous Glacial Lakes (PDGL) in Nepal 2020

Varibles →	**S_D**	**Class**	**Score**	**D**	**Class**	**Score**	**S_L**	**Class**	**Score**	**A_L**	**Class**	**Score**	**A_G**	**Class**	**Score**	**R**	**Class**	**Score**	**S**	**Class**	**Score**	**TVS↓**	**Remarks**
Varaibles weight →	**0.36**			**0.249**			**0.164**			**0.109**			**0.069**			**0.038**			**0.012**			**1**	
Glacial lake (past GLOF events) ↓																							
Tsho_rolpa_D1_01	6.124	0.5	0.18	0.15	0.75	0.187	2.119	0.25	0.041	1.45	1	0.109	15.08	1	0.069	0.038	1	0.038	0.012	1	0.012	0.635	V. high
Lower_barun_D1_02	6.04	0.5	0.18	0.811	0.5	0.125	7.136	0.5	0.082	1.12	1	0.109	9.02	1	0.069	0.038	1	0.038	0.012	1	0.012	0.614	V. high
Imja_Cho_D1_03	7.214	0.5	0.18	0.33	1	0.249	2.476	0.25	0.041	0.87	1	0.109	4.99	1	0.069	0.038	1	0.038	0.012	1	0.012	0.698	V. high
Lumding_Cho_D1_04	4.328	0.25	0.09	0.19	1	0.249	3.832	0.25	0.041	0.94	1	0.109	1.6	1	0.069	0.038	1	0.038	0.012	1	0.012	0.608	V. high
Chamlang_Cho_D1_05	19.81	1	0.359	0.17	0.75	0.187	21.18	1	0.164	0.79	0.75	0.082	0.33	0.25	0.017	0.038	1	0.038	0.012	1	0.012	0.859	V. high
Thulagi_D1_06	1.361	0.25	0.09	0.08	1	0.249	5.654	0.25	0.041	0.92	1	0.109	2.02	1	0.069	0.038	1	0.038	0.012	1	0.012	0.608	V. high
Nagama_Pokhari_D2_07	3.633	0.25	0.09	0.86	0.5	0.125	16.71	1	0.164	0.61	0.75	0.082	3.75	1	0.069	0.038	1	0.038	0.012	1	0.012	0.579	High
Hongu2_D2_08	9.808	0.5	0.18	0.06	1	0.249	22.99	1	0.164	0.74	0.75	0.082	0.49	0.5	0.035	0.038	1	0.038	0.012	1	0.012	0.759	V. high
Tam_Pokhari_D2_09	5.18	0.25	0.09	0.2	1	0.249	8.489	0.5	0.082	0.22	0.5	0.055	1.84	1	0.069	0.038	1	0.038	0.012	1	0.012	0.594	High
Hongu1_D2_10	7.787	0.5	0.18	0.315	0.5	0.125	6.356	0.25	0.041	0.22	0.5	0.055	3.9	1	0.069	0.038	1	0.038	0.012	1	0.012	0.519	High
kotam_gl_0193_D3_11	10.83	0.5	0.18	0.11	0.75	0.187	11.7	0.5	0.082	0.31	0.05	0.005	0.45	0.05	0.003	0.038	1	0.038	0.012	1	0.012	0.507	Medium
Gakal_gl_0004_D3_12	3.995	0.25	0.09	0.06	1	0.249	11.35	0.5	0.082	0.25	0.5	0.055	1.75	1	0.069	0.038	1	0.038	0.012	1	0.012	0.594	High
Barun_Pokhari_D3_13	2.965	0.25	0.09	0.29	0.75	0.187	5.372	0.25	0.041	0.31	0.5	0.055	3.65	1	0.069	0.038	1	0.038	0.012	1	0.012	0.491	Medium
East_Hongu1_D3_14	3.061	0.25	0.09	0.48	0.5	0.125	9.335	0.5	0.082	0.31	0.05	0.005	0.6	0.25	0.017	0.038	1	0.038	0.012	1	0.012	0.369	Low
Gabud_gl_0009_D3_15	4	0.25	0.09	0.96	0.25	0.062	27.54	1	0.164	0.25	0.5	0.055	6.59	1	0.069	0.038	1	0.038	0.012	1	0.012	0.49	Medium
Mera_D3_16	4.365	0.25	0.09	0.93	0.25	0.062	11.1	0.5	0.082	0.17	0.25	0.027	1.8	1	0.069	0.038	1	0.038	0.012	1	0.012	0.38	Low
koaru_gl_0016_D3_17	1.626	0.25	0.09	0.41	0.5	0.125	13.43	0.78	0.127	0.1	0.25	0.027	1.08	0.75	0.052	0.038	1	0.038	0.012	1	0.012	0.47	Medium
Gakal_gl_0008_D3_18	1.606	0.25	0.09	0.89	0.25	0.062	4.49	0.25	0.041	0.12	0.25	0.027	5.11	1	0.069	0.038	1	0.038	0.012	1	0.012	0.339	Low
kotam_gl_0111_D3_19	4.691	0.25	0.09	0.21	0.5	0.125	23.61	1	0.164	0.15	0.25	0.027	0.47	0.25	0.017	0.038	1	0.038	0.012	1	0.012	0.473	Medium
East_Hongu2_D3_20	3.4	0.25	0.09	0.16	0.5	0.125	9.137	0.5	0.082	0.16	0.25	0.027	0.28	0.25	0.017	0.038	1	0.038	0.012	1	0.012	0.391	Low
Kaligandaki_D3_21	2.281	0.25	0.09	2.4	0.25	0.062	2.664	0.25	0.041	0.67	0.75	0.082	1.78	1	0.069	0.038	1	0.038	0.012	1	0.012	0.394	Low

Note:- Area of these 21 PDGL is extracted from ICIMOD online portal, ICIMOD 2019.

6.3 The GLOF hazard mitigation; case studies

Nepal Himalaya is one of the most glaciated regions with the Hindu Kush Himalaya region. It has been identified as one of the global hot spots for climate change. One of the main concerns is glacial related hazard particularly GLOF although the frequency of GLOF occurrences is relatively low. The ICIMOD has identified over 2323 glacial lakes in Nepal (ICIMOD, 2011). During the second half of the 20th century, most of these lakes have emerged in response to raising temperatures as a result of rapid glacier melting (Yamada, 1998; ICIMOD, 2011). So, most of the present-day moraine dammed glacier lake did not exist before 1950s. there is strong evidence that the frequency of GLOF occurrences has increased in recent decades. It has been also indicated that the warming trend in Himalayan region has been greater than the global average (IPCC, 2012) it is highly likely that the risk of GLOF events will increase in the region in future.

The Himalayan region of the Nepal have relatively low population among other part of the country but is has huge contribution to the country's economy as its tourism is one of the main sources of income. Also, it is one of the most important sites for adventure tourism as the county has the top eight highest mountain in the world and is home to the Annapurna base camp and Mt. Everest. This research has examined the past event and various prevention measure after and before the GLOF events and analyzed them in order to identify the factor that helps to reduce the disaster risk and climate change adaptation. There have been very devastating GLOF events recorded in Nepal Himalaya. Some devastating events are Dig Tsho in 1985 and Tam Pokhari in 1998 as a result of the large volume of discharged water with sediment and debris resulting in the destruction of downstream flood plain and infrastructure. Currently, there are around 21 glacial lake identified as potentially dangerous glacial lake by the various organization in Nepal including ICIMOD. There have various risk reduction activities on these lakes and surroundings. So, in this chapter will investigate the risk reduction of the Tsho Rolpa lake (one of the biggest glacial lakes and potentially dangerous lake) and Imja glacial lake one of the most studied lake potentially dangerous glacial lake.

6.3.1 GLOF disaster Risk Reduction of Tsho Rolpa Glacial Lake

Tsho Rolpa glacial lake is one of the largest glacial lakes in Nepal. It is located about 110 km North-East of Kathmandu in the headwaters of Rolwaling Valley at the bottom end of Trakarding Glacier, at 4580 m above sea level. As glacial retreats and melts over time a moraine-dammed glacial lake is formed when moraines impound water behind them. Those moraine dams are naturally formed which are structurally weak and unstable in most of the case and they may contain ice core or unstable earthen materials in them. As a result, there is significant danger of a catastrophic failure. It is believed that the creation of the Tsho Rolpa is due to the stagnation and melting of the Trakarding Glacier (Rana et al., 2000; ICIMOD, 2009). Hence, GLOF disaster risk reduction was necessary at Tsho Rolpa glacial lake.

It is projected that Tsho Rolpa has been growing in size since the 1950s, from an area of 0.23 km^2 in 1959 (Yamada, 1998). In 2009 the lake had an area of 1.54 km^2 with a maximum depth measured around 133 metres and the volume of 85.94×10^6 m^3 (ICIMOD, 2011) (Fig. 6.2). It is clear that the lake has grown constantly due to the rigorous breaking away of ice at the terminus of Trakarding Glacier and it is the main inflow into the lake. The natural channel outflow can reach around 19m^3 during monsoon season. In winter the temperature around the lake can drop to -25^0C and by November the lake surface is frozen (Yamada, 1998). It is reported that there are around 7000 people leaving in the downstream of the Tsho Rolpa lake including Rolwaling and Bhote/Tama Koshi (Dahal, 2008).

The Nepalese government took swift decision to intervene and install the physical structure (lower the glacial lake level) and warning system to reduce the disaster risk and eventually saving the lives. The resident living in the close neighbourhood was also evacuated. It was one of the exemplary interventions by the governments in the HKH region. This proactive action by the Nepalese government also portrays success and failure. The decision taken by the government is not necessarily GLOF hazard mitigation strategies in long term but rather disaster risk reduction strategies to minimize the damage to the infrastructures and people's livelihood should disaster occur. The case still remains the same but since we know more now, the lessons can be learned for the governments and other regional stakeholders confronted with this challenge to make the decisions due to the threat of GLOF.

6.3.1.1 Water level reduction by instillation of physical structures

In May 1995, the Nepal- Netherlands Friendship Association initiated the work to install the siphons in the Southwestern part of the moraine dam to reduce the lake water level. Specially designed siphons were donated by a company called Wavin Overseas, Netherlands (Rana et al., 2000). After two years, five locally manufactured siphons (two with double inlets and three with single inlets) were installed by the Nepalese government to augment the siphons installed by Wavin Overseas B.V in 1995. The test siphons worked satisfactorily with some maintenance in the high altitude and freezing conditions. But later further installation was aborted due to funding issues and due to the lack of the space to install the large number of pipes as required. In 1998, as suggested by the national and international experts, Netherlands and government of Nepal signed the grant agreement to the Tsho Rolpa Lake Outburst Flood Risk Reduction Project (DHM, 1997). The objective was to reduce the lake water level by 3m by cutting an open channel in the Southeast part of the end moraine which could immediately reduce the risk of the breach formation on these natural moraine dam.

Figure 6.2 Tsho Rolpa lake, water level reduction project, Nepal (Lamsal et al., 2015)

The construction work started in spring of 1999 and was completed by the middle of July 2000, lowering the lake level by 3 m in technical consultation with Reynold Geo-

Science Ltd, UK (RGSL). As the lake was situated at an altitude of 4,500 m and is 60 km from the nearest road the construction work was challenging as all the materials and equipment had to be transported in by porters or helicopters and, in the case of larger machinery, re-assembled at site as necessary. The final channel was lined with a geotextile membrane overlain by gabions. For additional erosion protection, boulders were chained together at the downstream end of the channel. To achieve the drawdown in controlled manner a gate was installed. The RGSL monitor the physical environment to ensure that the work had no adverse effect on the glacier or moraine dam throughout the construction process.

Figure 6.3 Constructed dam and water sluice gate in Tsho Rolpa glacial lake reduction

6.3.1.2 Installation of Early Warning System

United Nation defined the early warning system as: The provision of timely and effective information, through identified institutions, that allows individuals exposed to a hazard to take action to avoid or reduce their risk and prepare for effective response (UNDP, 2017). The early warning system must integrate knowledge of the risks, monitoring services, dissemination and response capability. The early warning system need to be simple to operate, easy to maintain, technically sound and reliable.

The maximum effect can be achieved if the system can be run and maintained by the local communities.

In June 1997, a manual warning system was installed in Tsho Rolpa glacial lake by government of Nepal. The security posts were established temporarily and provided with communication set so that they can inform inhabitants in a timely manner of downstream locations, as well as the Khimti Hydropower Project. The Department of Hydrology and Meteorology also installed the meteor burst system before the monsoon of 1998, a type of early warning system, to provide the inhabitants of the Rolwaling and Bhote/Tama Koshi Valleys with early information about a GLOF. This will give them enough time to evacuate and reach to safe location. It consisted of a glacial lake outburst flood sensing system located just downstream of the end moraine as a flood is sensed, the warning is relayed to 19 stations positioned downstream, fitted with audible alarms (Fig. 6.5). This automated early warning system was established with financial support from the World Bank.

Despite all these effort as of 2002, the system was no longer operational, in part because local residents presumed that the water level at lake had been reduced to a safe level. The system has been damaged due to political unrest and as infrastructure has been built in the road recently (Ives et al., 2010).

Figure 6.4 Tsho Rolpa's early warning system (Shrestha, 2002)

6.3.1.3 Evacuation of Downstream Residents

In the summer of 1997, the evacuation order was issued for the people living in the downstream of the Tsho Rolpa glacial lake due to the GLOF risks. Those residing on the bank of the Rolwaling river were evacuated (Dixit and Gyawali, 1997). Around 6000 residents were moved into safer place for at least for one month. They moved 20m up from river bank (Dahal, 2008).

6.3.2 Imja glacial lake lowering project

Imja Tsho is a supraglacial lake situated in the Khumbu region, formed on top of Imja glacier, and it is confined on the East by the Lhotse Shar and Imja glaciers, on the North and South by lateral moraines. The natural outlet on the terminal moraine dam feeds in to the Imja Khola (river) (Somos-Valenzuela et al., 2013). The lake is classified as one of the 20 most dangerous glacial lakes (ICIMOD, 2010) and one of the high-risk glacial lakes in Hindu Kush Himalaya Region. Before 1960 satellite images at the time show only few small supraglacial ponds which indicate that the Imja lake did not exist before that period. The area of the lake grew rapidly from 0.3 km^2 to 0.86 km^2 between 1975 and 2002 (Bajracharya et al. 2007). ICIMOD (2009), indicated that rate of retreat of the Imja Glacier is among the highest recorded in the Hindu Kush-Himalayan region at an astounding 42 meters per year between 1962 and 2009. By 2012 the volume had increased to 61.7±3.7 million m^3 (Somos-Valenzuela et al., 2014) while in 2012 it had a volume of 35.8±0.7million m^3 (Sakai et al., 2007).

People living in the vicinity of the confluence of the Imja glacial lake will be directly affected by GLOF if one should occur. There are around 12,184 people residing within the 5-village development committee and they will be directly affected. This rural mountain community mainly depends on environmental resources such as forest, fisheries and eco-tourism industry. Partial and full damage to these expensive mountain's infrastructure will make adverse effects on these communities. Many trekking routes including the trails that follow the bank of Dudhkoshi are also exposed to Imja GLOF. Hence the region offers tourism-based employment opportunity not only for its local people but also for people living in adjacent districts. All the livelihood options such as tourism, trade and business, planned infrastructure project (hydropower plant) agriculture and livestock are directly or indirectly affected by a potential GLOF event leaving considerable socio-economic damage. It is estimated that the economic impact of the events will be equivalent to about USD 11.89 million under modelled flood scenario and USD 35.5 million under assumed maximum level of flood (35 m high from the river bed) (Khanal, 2009).

Hence, there are urgent needs to address the looming threat of the potential GLOF from Imja. Nepal government deployed the Nepalese army with help from UNDP to reduce the lake water level by 3 metres in 2016. The Department of Hydrometeorology, government of Nepal in technical and financial help (USD 7.2) from the UNDP (United Nations Development Programme) and the Global Environment Facility deployed the Nepali Army to conduct the lake reduction processes. The Community Based Flood and Glacial Lake Outburst Risk Reduction Project (CFGORRP) was designed to lower potential loss of human lives and infrastructure from a glacial lake outburst flooding in Solukhumbu and the downstream floodplains.

6.3.2.1 Lake lowering scenarios

The model proposed by Somos-Valenzuela et al., 2015 was used to assess the potential flood reduction at Dingboche. This model was run with lake levels 3, 10 and 20 m lower than the current water level of the lake by then the hydrographs and flood stage, respectively, at Dingboche for the 0, 3, 10 and 20 m lake lowering scenarios can be seen in Figure 6.5. As the lake lowered by 3 m about 8.6 ha of farmland and 25 structures are impacted by the flooding. In contrast, lowering the lake 10 m results in a 14 and 36% flood height decrease, respectively, at Dingboche, with respective peak flood heights of 19.2 and 14.4 m. These lakes lowering scenario will lead to the significantly less flooded area particularly 20 m lowering scenario, this will reduce the flooded area significantly. The flood in 20 m scenario will stay within the historic flood plain of the river (Somos-Valenzuela et al., 2015). But despite that they decided to lower the lake 3 m, probably due to the cost benefit analysis and feasibility of the scenario.

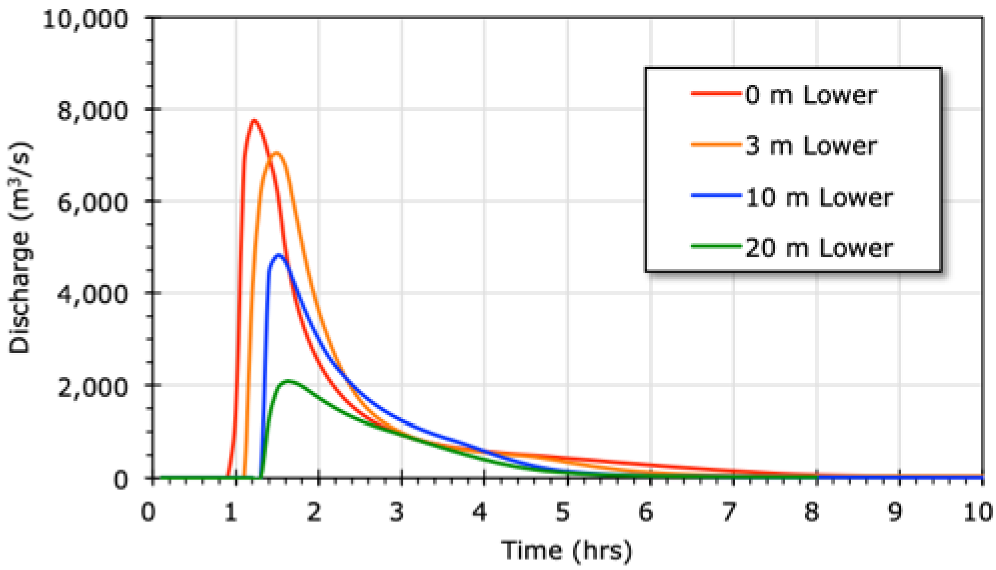

Figure 6.5 GLOF hydrographs at Dingboche under current lake conditions for 0, 3, 10 and 20 m lake lowering scenarios (Somos-Valenzuela et al., 2015)

Figure 6.6 Dingboche Imja lake area and river (ICIMOD, 2011)

6.3.2.2 Community-based GLOF Early Warning System

The project also implemented the Community Based Early Warning System (CBEWS) that is easy to maintain with low cost and easy to use. They have installed manual river gauges, sirens and distributed hand mikes to the local task force to the downstream communities at Imja lake. They have also installed automatic Weather Station and GLOF sensors at Lake area, audio GLOF sirens, slave and siren nodes and services for upstream as part of GLOF early warning system (GLOF EWS). They have also identified safe evacuation locations schools, monasteries and open spaces. The project has also provided training to the local community on Early Warning (EW), Light Search & Rescue and First Aid (FA) which is thought to be useful to raise the awareness and increase community capability to manage the disasters (UNDP, 2015).

They have also addressed some cultural issues that were associated with lake lowering project and CBEWS, they believe their god/goddess lives in the lake so the worship ceremony (puja) was performed before the construction work began co-ordinating with local community. The project also hired local project staff to monitor the system daily. These are people with knowledge of the local language, context and culture. This is thought to be helpful for community mobilizations.

6.3.2.3 GLOF Risk Management Skills and Knowledge transfer

The Imja lake lowering project also focused on increasing the capacity of local and regional stakeholders. They ran some training programme to educate and prepare the general public and local institution on disaster preparedness and GLOF risk management. They initiated the creation of a local GLOF Risk Management Coordination Committee (GRMCC) comprising of 19 members representing BZMC, SNP, District Administration Office, Army, Police, Health, Red Cross Society, Monastery, Community Forestry, Local Groups and Women Committees. They were accountable to communicate GLOF warnings and to coordinate GLOF risk reduction activities in the area. There was local information and knowledge distribution center where they can provide audio-visual knowledge and materials flyers, brochures and posters regarding GLOF hazard and preparedness to the local people and anyone interested. The information was provided with Nepal and local language (Sherpa dialects).

The activities and mobilization of the local institution including GLOF Risk

Management Coordination Committee (GRMCC), Village Development Committee (VDC) and buffer zone management committee area anticipated to continue. These initiations have been provided with clear pathway for their sustainability and reasonable administration by coordinating with local, regional and central government.

6.3.3 Comparative analysis of Tsho Rolpa and Imja lake lowering project

Tsho Rolpa and Imja, are both glacial lakes which were identified as potentially dangerous glacial lake by various agencies including Department of Hydrometeorology (DHM), UNDP. The severity of the GLOF mainly depends on the exposure of the land, people and infrastructure on the downstream flood plain. There are more than 96 thousand inhabitants living in the downstream flood plain of Imja lake up to 120 km from the lake while there are more than 140 thousand inhabitants living downstream of the Tsho Rolpa lake up to 100 km from the lake (Khanal, 2011). In this regard Imja GLOF poses significant risk of damaging greater populations and infrastructure. Total economic value of the possible risk and damage from an Imja and Tsho Rolpa could be USD 8.98 billions and USD 2.4 billions as shown table 4 below (ICIMOD, 2011).

Tourism and hydropower project are in high-risk zone within flood plain of the Imja glacial lake. Possible GLOF from Imja would not only threaten the livelihood of the local residents but also it will put the critical tourism infrastructure in grave danger such as road, bridges, trekking trails, teashops and guesthouse. The flood plain of the Imja lake also serve the Everest base camp that is main entry point for the trekkers on the route. Such damage would have a huge socio-economic impact to the society and their livelihood that may take years to rebuild. It is estimated that more than one thousand hectares of land will be directly affected by a possible GLOF from Imja lake. Hence, based on this information it can be justified that the extra attention and priority be given to Imja GLOF reduction and disaster risk management.

The GLOF disaster risk management and prevention programme on both glacial lakes not only helped to rescue the people at immediate danger but also helped to build resilience in agriculture, hydropower and tourism. Since the disaster risk management programme on Imja glacial lake was implemented in 2016 and onwards the success rate of the prevention measure can only be evaluated after continuous monitoring and further investigation. While the prevention measures at Tsho Rolpa glacial lake were considered a success, it was not all successful due to various reasons including failure of unfunctional warning system, political unrest, communication gap between local stakeholders.

The imminent threat from the Tsho Rolpa glacial lake and the warning from the government agencies were largely ignored and dismissed by the residents as "mere rumour" (Dixit and Gyawali, 1997). As a result, the relocation on the residents within the flood plain of the glacial lake and implementation of the early warning system was not successful. This is partly due the disinformation and exaggeration by the media and in part to the local and cultural norms about risk precipitation (Dahal, 2008). This unsuccessful relocation of the local people also has negative impact on implementations of early warning system. After 4 years of the installation, it was no longer in use despite having robust and latest technologies. The political unrest was also to blame as it reduced the institutional capacity to maintain the early warning system and update the training to the locals. Uncertainty regarding the GLOF occurrence and prediction also went wrong in the past as the literature and scientific investigation regarding the GLOF are relatively new. The reports declaring that Tsho Rolpa was to burst in the 1997 had been considered baseless by locals (Dahal, 2008). Hence, the future GLOF disaster reduction and mitigation project needs to address these factors which may led to policy change and the advancement of interventions to contend with glacial lake outburst flood,

Table 6.3 Potential damage caused by the GLOF

Description	Imja (120 km)	Tsho Rolpa (100 km)
Population potentially directly affected due to loss of resources	96,767	141,911
Population potentially indirectly affected	501,773	524,323
Exposed Hydropower investment potential (Billions USD)	8.98	2.4

6.4 GLOF hazard mitigation and climate change adaptation

According to United Nation (UN) hazard can be defined as a process, or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation. Hazards could be single, sequential or mutual in their origin and effects. According to their location, intensity or magnitude, frequency, and probability any hazard can be characterized. A natural hazard is the threat of a naturally striking event which may cause damage to the environment and the people. The GLOF is also cascading events of the other glacial related hazard and adverse weather condition. So, the GLOF hazard management will be discussed in this section.

The natural hazard management can be defined as the process of planning, implementing, evaluating and adapting strategies. The procedure and measures related to analysis, reduction and transfer the risks with aim of reducing the hazard and vulnerability (IPCC, 2012). It is a continual process that comprises both physical and non-physical measures that takes underlining risk factors within society. This aims to elude the risk by advancing resilience to the effects of the disaster that supports the sustainable development. Any hazard could easily turn into the disaster if the precautionary measures are not be taken. Thus, GLOF hazard management is very important in order to manage the hazard in short-term and reduce the probability in longer term by implementing mitigation measure.

Glacier hazard management particularly the GLOF, mitigation should be planned based on the local geomorphology, socioeconomical, sociopolitical and environmental factors. Based on the case study of the Imja and Tsho Rolpa GLOF hazard management of the region has been qualitatively analyzed. The evaluation is based on the success rate of the implemented measure to the risk reduction and adaptation. The likelihood of the natural hazard occurrence and its exposure to the people and livelihood can be defined as the risk while adaptation is actual adjustments made due to the observed or prescribed change to the climate. Thus, the GLOF hazard management, mitigation and climate change adaptations involve various elements. It is vital to identify and predict the hazard due to the environmental change so that the correct engineering strategies (removing all exposed populations, property, and infrastructure from potential hazard zones) can be implemented in order to reduce the damage to the livelihood of the community.

From the past events and case studies the socio-environmental measure found to be the most important measure in order to implement both soft-core and hard-core engineering solution that have been prescribed or observed (Adger et al., 2009b). Any policy implementation or certain decision has to be in line with understanding of the community or their adaptive capacity. To understand this, it is necessary to identify what are the risk reduction measures and why it has been implemented or obstructed. The glacial hazard management measures and factors that facilitate or obstruct those measures will be examined further in this section (Fig. 6.7).

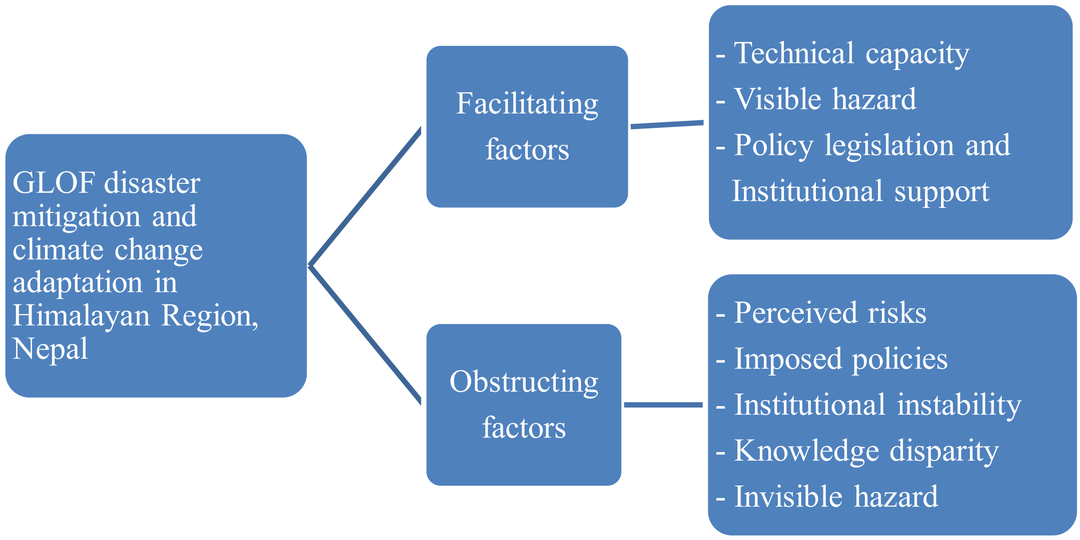

Figure 6.7 Analysis of GLOF disaster mitigation in Himalayan Region Nepal

6.4.1 Facilitating factors for GLOF hazard mitigation and climate change adaptation

From empirical evidence it is clear that the GLOF hazard management and climate change adaptation are not one-time events. Rather it is ongoing event that need continuous adjustments, evaluation, monitoring, public awareness, progressive learning and participation of the stakeholders and decision makers in local, regional and national level. The following factors that help to implement the observed or prescribed disaster risk reduction and climate change adaptations measures.

- Technical capacity
- Visible hazard
- Policy legislation and Institutional support

6.4.1.1 Technical capacity

Any disaster caused by the natural hazard is mainly the consequence of the socio-economic and political activities rather than “natural” phenomenon. However, this process involves the physical environment which generates the floods, flash floods and avalanches (Wisner et al., 2004). Subsequently, engineering and technological solutions including early warning systems, hazard maps, meteorological information, building materials, and building codes, environmental knowledge play major roles in risk reduction and climate change adaptations.

In the Himalaya region science and engineering have significantly contributed to understanding the glacial hazard and its dynamics partially studying, monitoring and emptying the potentially dangerous glacial lake into the region. The engineering efforts to partially emptying the Tsho Rolpa and Imja has been a single most effective strategy. Collective scientific knowledge and research activities around the world allowed to identify the potentially dangerous glacial lake which motivated the national and international stakeholders to allocate the resources to conduct the mitigation measure immediately. That convinced the engineers to seek the technical solution to address the imminent threat at the same time look for the long-term adaptation plan. These measures were only possible due to the technical capability that involved engineering experience and environmental knowledge.

This technical knowledge and experience of GLOF mitigation measures are extremely important. As of the 1998, government of Nepal, Netherlands Development Agency (Neda) and Reynold International (engineering consulting form) had experience of taking such measure to mitigate the GLOF hazard. However, each challenge is unique. Building on the experience, government of Nepal, Department of Hydrology and Meteorology (DHM) drained Imja glacial lake by 3 m in 2016. It is largely regarded as successful project. Their experience from the previous project also persuaded them to drain the lake slowly and safely using four progressively deeper drained tunnels. Without detailed knowledge and experience from other glacial lakes throughout the Himalayan region, the Imja lake lowering project might have progressed contrarily, perhaps with devastating consequences.

6.4.1.2 Visible hazard

Often the disaster mitigation measures are reactive because the early warning systems, hazard zoning, and other risk reduction measures are employed only after catastrophic events. People's experience with the disaster can inspire the risk reduction measure and prompt to do more if anyone has first-hand experience of dealing with the disaster. They are also more likely to support the mitigation measure and climate change adaptation programme (Whitmarsh, 2008). So, natural hazard with visual signs is highly likely to affect the people's perceptions of the risk and their likelihood of the disaster risk reduction measure and climate change adaptation. Apart from the visibility and people's experience, the environmental circumstances, economic constraints, political forces, social relations, or cultural values also determine the people's attitude towards the natural disaster and its mitigation measure. The visible hazard with public awareness often catches the stakeholder's attention quickly to address the mitigation measure.

In the Himalayan region, series of the glacial related disaster and the presence of the visible threat made the implementation of GLOF hazard management and mitigation measure as matter of urgency. These visible hazard and series of the disaster events affected the local population, authorities and stakeholders differently as they calculate the risk differently. There GLOF events in the Nepal Himalaya became frequent from around 1970. Since that various GLOF hazard mitigation, risk reduction and management measure has been taken. In Nepal the most crucial advance in GLOF hazard management taken after Tsho Rolpa glacial lake posed greater risk to the community as water level increased significantly due to glacial retreat and other various reason. The lake lowering project was overall a success that completed in 1990s.

It is evident that the visible hazards and its publicity can inspire the locals and the responsible authority to respond to some degree. They will be held more accountable as public awareness spread. The Imja lake lowering project, 2016 was widely covered in the newspapers, online media and blogs discussions. In 1997 after Reynolds International's report to lower the Tsho Rolpa lake as GLOF mitigation measure, it drew enormous media attention. The authority's reaction was centred on scientifically-based recommendations from experts in the field. Both local and international media attention are also believed to have contributed to the government's proactive move to mitigate the GLOF threat from Tsho Rolpa Lake (Dixit and Gywali, 2007). The case of the Tsho Rolpa GLOF mitigation project showed that the experience with disaster events and visible hazard does encourage the authority's response, however it is very difficult to convince the local population of the perceived natural hazard. Because the people living in those disaster-prone regions tends to take their decision based on a complex calculation of different risk perceptions (Carey, 2008).

6.4.1.3 Policy legislation and Institutional support

There is long history of the GLOF occurrence in Nepal. Some evidence shows that the GLOF occurred in Nepal about 450 years ago (Dixit and Gyawali, 2007). There are seven major glacial lake outburst floods which have occurred in the country since 1964 (Shrestha, 2018). In Nepal, the GLOF initial drew the attention of scientists and stakeholders only after the catastrophic outburst of the Dig Tsho Glacial Lake. The outburst had significant economic losses and destruction to infrastructure, including a newly built hydroelectric power station, 14 bridges, more than 25 houses and agricultural lands worth four million dollars (USD), many lives were lost (Dahal, 2008).

Currently, there is no key policy that is directly targeting GLOF risk management in Nepal. Nevertheless, the Nepal Disaster Relief Report 2009 suggests that, there is some sort of intra-governmental coordination for the management of flood-related disasters in Nepal. The flood disaster management includes prevention, preparedness, rescue and relief. Reconstruction and rehabilitation also come under the disaster management in Nepal that can be applied to glacial lake outburst floods as well. Currently, the DHM under the Ministry of Population and Environment manages the glacial lake outburst flood. But different government agency and institutions have been involved in various stages as per necessity including, security agencies, Ministry of Home Affairs, and Department of Water Supply. In terms of the policies, Nepal do not specifically target glacial lake outburst flood risk management, but they do acknowledge GLOF within the strategy as a whole for flood risk management. However, they may have strengthened Nepal's competence to manage flood-related disasters (Shrestha, 2010).

Financing is another critical role that institutions can play by both providing funds in the first place or by directing them to specific projects from diverse sources. Often governmental department are criticized for not allocating enough funds for the disaster risk and reduction and presentation. But it has been coordinating with various international and regional organizations for the financial assistance, including UN, UNDP, ICIMOD, USAID, UKAID and different scientific and research organizations.

6.4.2 Obstructing factors for GLOF hazard mitigation and climate change adaptation

Until recently, the research examining the obstructing of GLOF hazard mitigation and climate adaptation mainly centred on the ecological or physical and socio-economical limits. However, this approach is too narrow as they fail to examine the role of the risk perception, culture, ethics and traditional knowledge (Adger et al., 2009b). Failure to address those issues can derail the adaptation and hazard mitigation measure that has been regarded as a success in its initial phase. For example, the early warning system in Tsho Rolpa was installed in 1997 and not functional after few years due to political instability. These are the obstructing factors to implement the disaster risk reduction and climate change adaptations.

- Perceived risks
- Imposed policies
- Institutional instability
- Knowledge disparity

- Invisible hazard

6.4.2.1 Perceived risks

The nature of the risk perception in natural hazard is dynamic, often marginalized populations and deprived communities are generally at the most vulnerable situation to the natural hazard and highly likely to be affected by climate change and global warming (Eriksen and Kelly, 2007). In most case these communities get pushed in to exposed areas and have very minimal governmental protection and support for recovery as they experience the catastrophic events. Yet the communities should not be considered as passive victims unable to respond to the changing climate. Because the climate change adaptations are complex. These vulnerable communities consist of the complex individuals who categorise the risk and the potential impact of the adaptation based on their socio-economical standing, values, worldwide views and daily behaviour (Paton et al., 2010). This has created the major discrepancies between locals and policy makers when it come to the climate change policy implementation and adaptations in case of Tsho Rolpa GLOF mitigation project, Nepal.

An evacuation of residents living at the downstream of the Tsho Rolpa glacial lake, mainly residents living on the banks of the Rolwaling River banks was carried out as Tsho Rolpa was predicted to burst in summer of 1997. The local residents responded to the call and moved 20 m away from the river bank. Around 6000 (74%) of the local residents were evacuated and relocated to relatively safe place (Dixit and Gyawali, 1997). However, the relocation plan and early warning system was not successful as residents started to return to their homes. Despite have robust early warning system and latest technology in place (still standing as of today), it is not functional anymore while GLOF threat is looming. The imminent threat posed by the GLOF was perceived as mere rumour by some locals and this perception started spreading. Some believe that the media is exaggerating the facts and cultural norms regarding the risk perceptions (Dixit and Gyawali, 1997). These perceived risks associated with evacuation plan and early warning system outweigh any benefits residents saw from the evacuation and early warning system. There are other more pressing issues than the environmental changes around them and global scale. This has hindered the plan to achieve community resilience in long-term.

6.4.2.2 Imposed policies

Despite having robust plan and strategies, without the appropriate policy in terms of sustainable implementation it will fail nevertheless. Defining the risk is in itself an act of power. The way risk is framed instantaneously suggests certain solutions to reduce risk (Slovic, 1999). The response to the natural hazard and climate related disaster must be situated within the broader socio-political context that guides the decision makers and risk perceptions. Additionally, people often reject information about hazards and do not take scientific assessments or government warnings at face value when risk reduction or adaptation initiatives threaten their autonomy (Paton et al., 2010). Even a well-intended hazard mitigation plan may be opposed by the locals if they perceive it differently to what is imposed by the higher authority.

It is evident that the imposed policy on hazard mitigating will not be effective as it intended to be, research has shown from around the world. The locals opposed central government's GLOF mitigation plan and hazard map zoning in lake 513 at Lima, Peru around 1997. The lack of consultation with locals by government authorities and engineers is to blame for the failure. So, the locals perceived the relocation policy as an imposed agenda meant to take land from rich and give it to poor (Walton, 1974). Simply they did not trust the central government, making it worse the local government never embraced the idea of GLOF mitigation and presentation policies, thus leaving central government in charge of the glacier hazard management plan.

A similar situation has occurred during the Tsho Rolpa glacial lake lowering and GLOF mitigation (1995-1998) project. Government agencies failed to convince the locals on GLOF mitigation and risk reduction and evacuation plan due to various socio-economic and political reasons. As a result, the locals observed those policies as imposed agenda by the central government. This has contributed to the ongoing de-legitimisation of government science in the minds of the public, mainly because of the lack of transparency and low accountability in how it does science. Moreover, the government plan and strategies seem to be incomplete. They have asked locals to move 20 metres above the river bank without providing any support or guidelines to move to possible sites. This is due to top-down approach on GLOF mitigation policy with the central government unable to cater to the needs of the locals.

These imposed policies thus impeded GLOF hazard management and mitigation strategies because the population remained exposed to glacier hazards. To improve the community resilience and GLOF mitigation plan in long term the policy makers, engineers and consultants need to engage with local grassroot communities through public dialogue, discussion and taking bottom to top approach in policy making and sustainable implementation.

6.4.2.3 Institutional instability

Institutional instability is another reason why GLOF mitigation has not been achieved on the GLOF prone regions. Often in the developing world, the political instability causes various problems in terms of institutional instability and science policies. The effective institutions can increase adaptive capacity, institutional instability can restrain disaster risk reduction and climate change adaptation (Eakin and Lemos, 2010). The institutional instability may delay the project which may then lead to the project failure and increased the risk over the time. The financial instability is another major problem that may be caused due to the instable institution, hindering the GLOF mitigation. Without proper funding for equipment and manpower and expertise as well as the absence of research and development and project guidance, the projects might derail and limit the possible solutions. This phenomenon has been seen around the world, particularly in Nepal.

In Nepal, political unrest became more frequent since 1998, that resulted in a lack of institutional capacity to maintain the systems at various government agencies in Nepal for a long period (Dixit and Gyawali, 1997). The insurgency in the country can also be blamed to some extent as this delayed routine maintenance of the early warning system that has been installed in Tsho Rolpa glacial lake in Nepal. Since the government's priority has been shifted, lack of financial stability was a major issue for maintaining and operating the warning systems as they require monitoring and maintenance on a frequent basis. As a result, the system has gradually deteriorated to its present non-functional state (Shrestha, 2010). Moreover, a small flood impaired the glacial lake flood sensor, and gradually, it has been reported that the equipment from the warning stations has been either disappeared or vandalized. Solar panels and batteries were the first to vanish.

In the past GLOF has originated in Tibet (China) and caused adverse effects in Nepal and vice-versa. Since this is the transboundary issue, regional and local governments should work together to tackle these issues. But institutional and political instability makes is harder to work together in common policy and strategies to mitigate the GLOF hazard in the region.

Thus, institutional instability led to a diminished capacity for technical, scientific, and mitigation measures. More widespread government instability also affected popular opinions of the climate change adaptation, GLOF hazard mitigation and various government projects more broadly. These changes have eroded public confidence in government agencies, including the glaciology division, and hydro-meteorology department thus increasing vulnerability to glacier hazards.

6.4.2.4 Knowledge Disparity

The limited knowledge and scientific uncertainty with divergent knowledge systems that distinct social, or specific groups possess may refer to knowledge disparity in the community. Thus, this disparity affects the knowledge about both human and environmental systems within the community. Despite robust scientific research and findings, its dissemination and how the society and its mechanisms perceive the "new knowledge" may contribute towards knowledge disparity. There are various dynamics that influence how the society and its mechanisms perceive the new knowledge. But due to the nature of the problem, study of glacial hazard and its dynamic are less advanced than others within the scientific and engineering community.

The key challenge to manage the GLOF hazard is its uncertainties. These uncertainties exist due to fairly advanced field of glaciology and nature of the problem itself. The level of the uncertainties or level of knowledge can be divided into two. Firstly, the main uncertainties refer to the glacier retreat and glacial lake formation and surrounding geomorphology. The documentation of the glacial retreat has started from twentieth-century (Racoviteanu et al., 2008) but there is very little information prior to that around the world including Himalayan region, Nepal. The hazardous potential of the Tsho Rolpa glacial lake was identified as early as 1987 (Gyawali and Dixit, 1997). The existing PDGL in Nepal has been extensively studied by ICIMOD and DHM in Nepal. But explicit spatial data regarding all past events and possible future retreat are lacking. But in the Alps, the complex methodology has been established to assess the ice thickness and detect the future lake formation over the time (Frey et al., 2010). Nevertheless, the timing and actual formation of the lake are still uncertain however it expands the scientific knowledge and understanding of the GLOF dynamics and this could be applied to the Himalayan region Nepal.

The greater degree of uncertainty exists for the second types of the knowledge, that is related to the mass movement or slope instability with the region including ice/rock avalanches, moraine dam failure, rock slope failure or combination of these. Moreover, the understanding of the stability of steep ice and bedrock is still limited (Carey et al., 2012). It is evident that the climate extreme (both precipitation and rising temperature) has adverse effect on the glacier and its surroundings and it greatly affects the slope stability and can initiate the mass movements (Huggel et al., 2010). The precise slope failure and its time are extremely impossible to predict however. There are several GLOF events recorded due to the slope movement around the world including the Himalaya region. Hence, the knowledge of the future GLOF occurrence, timing and new glacial lake formation is limited. Thus, to cope with different level of uncertainty and knowledge disparity within all stakeholders it is vital to focus on GLOF hazard mitigation and climate change adaptation in the region.

There is also disparity among stakeholders about what constitutes appropriate knowledge to be relied upon for decision making. The early warning system installed in Tsho Rolpa glacial lake, Nepal has been dysfunctional after few years of installation and there was disagreement between different stakeholders regarding the level of water to reduce in the Imja lake lowering project in Nepal. The institutional instability, changing social relations and unreliable risk perceptions by different groups are difficult to predict and thus can hinder the implementation of appropriate climate change adaptation measures.

6.4.2.5 Invisible Hazards

Invisible hazard is one of the obstructing factors for the glacial hazard mitigation. The research suggested that the traditional method e.g., photographs and videos is a more effective method to convey to the general public and stakeholders than the technical drawing and 3D maps (Haynes et al., 2007). However, it is also evident that the public do not alter their behaviour even when the invisible hazards are identified and experienced by the people (Whitmarsh, 2008) rather they are more likely to generate complacent behaviour. In contrast if visible hazard is communicated particularly with disaster experience, they are more likely to comply with the disaster mitigation agenda and climate change adaptation agenda.

Mainly, the invisible hazard can be described in two aspects first, unidentified hazard and second, identified but invisible to the general public and some stakeholders. The GLOF hazard in Tsho Rolpa lake, Nepal was identified as early as 1987 by engineers and scientists but it was invisible to general public until few years later when water level in the lake visibly increased. Most of the glacial lake hazard in the Himalaya and around the region are invisible because those lakes are formed by natural dam either by moraine or rock. In both cases it is very difficult to understand the true extent of their condition. Sometimes the glacial lake dam is formed by the dead-ice underneath which is invisible at the beginning. This applies to the glacial lake from the other parts of the world as well. At lake 513 in Peru, the glacial lake was not regarded as dangerous until it suffered GLOF in 2010 as lake freeboard was more than 20 m (Carey et al., 2012). The actual hazard was underneath the glacial ice height above the lake on Mount Hualcán, Peru which was not identified by the authorities and other stakeholders giving them the false impression that the lake was secure. Thus, continuous monitoring of the area with changing environment and climate condition is vital to mitigate the GLOF hazard while minimising the exposure to the human settlement.

6.4.3 Holistic approach to GLOF hazard mitigation and climate change adaptation

Across the HKH region temperature is set to increase by at least 1-2°C by 2050 (Shrestha et al., 2015). The prediction is even higher at the greater elevations. In most of the places the winters are predicted to grow warmer at a higher rate than summers. The extreme weather events including intense rainfall leading to flash floods, mass movement (avalanches, rock-fall, landslides), drought is likely to increase its frequency and magnitude. So, precipitation is very unpredictable and spatial variability is very high. And this may ultimately trigger the GLOF. These extreme events have various adverse effects to the communities and human settlement. The livelihood of the marginal and poor communities is set to be hit the hardest by the human induced climate change and global warming in the region.

The climate change adaptation in the high Himalaya region is becoming increasingly urgent and important. The geomorphological conditions and extreme weather patterns of the region presents unique sets of challenge in climate change adaptions (Shrestha et al., 2015). The research shows that these invariable extreme climate events already affect the people's livelihoods in the region. The agricultural production has decreased over the year due to the drought, high temperature, flash flooding. The colossal impact of these extreme weather events on the people's livelihoods in the region highlights the urgency of the situation and need of climate change adaptation. But the level of understanding of adaptation needs and interventions in the mountainous region are very limited due to insufficient knowledge of climate change impacts on the people and ecosystems. Being classified as Least Developed Countries (LDCs) in Nepal most of the mountainous people live in poverty with lower human development index (HDI). Thus, for mountain people in Nepal, impacts of the climate change bring a significant risk of undermining the achievement of fundamental human rights including health, food, housing, and access to drinking water.

Apart from climate change there are other several driving forces such as political unrest, population change, economic growth, urbanizations, globalization contributing rapid socio-economic transformation in Nepal. These driving forces have complex interaction with each other. Thus, the process of these changes is highly uncertain. In these circumstances the leadership and stakeholders need to go beyond incremental strategies and initiate transformative development and adaptation plans. In Nepal, transformational change is urgently required to enable mountain women, left behind because of male out-migration, to emerge from being 'frontline victims' of climate change impacts to become 'risk and resource managers' with control over productive assets. The policy maker needs to build the capacity to understand growing needs and address those with innovative solutions. But these are only achievable if stakeholders and political leadership drive for strengthening of the adaptation responses within a greater transformative development regime.

Thus, disaster risk reduction and community resilience are the only way forward. These disaster risk reductions involve activities aimed at reducing such losses by addressing hazard related risks and reducing people's vulnerability. The structural mitigation measure with hydraulic engineering method for lowering the lake as required and Community-Based GLOF Early Warning System are the major elements of disaster risk reduction. It saves life and reduces socio-economic impact caused by the disaster. To have sustainable outcome of these measures, community involvement is paramount. That can be achieve by active involvement of the communities, a strong public education on awareness of risks, and an effective communication system that ensure a constant state of preparedness. The lesson can be learned from the Tsho-Rolpa and Imja Glacial Lake Outburst Flood Risk Reduction Projects and that can be replicated to the other parts of the Himalayan region.

6.5 Conclusion

The natural hazard mitigation and climate change adaptation is a complex process. It needs to be addressed at the policy level with advanced research and scientific investigations with emphasis into the implementations by national, local and regional stakeholders. Thus, it is out of scope of this research to investigate the whole process but the following conclusion can be drawn in terms of GLOF hazard management and climate change adaption.

In the Himalayan region snow fields and glaciers can be hazardous. Due to climate change, the global temperature is set to continue rising in the near future. One of the significant consequences to the Himalayan community is glacial related hazard, particularly GLOF. As glaciers retreat due to climatic warming, the number and volume of potentially hazardous moraine-dammed glacial lakes in the Himalayas is rising. Those newly formed lake behind unstable ice-cored moraines or those of the existing glacial lake have the potential to burst devastatingly, producing distressing GLOF. In some cases, the discharge rates of 30,000 $m^3 s^{-1}$ and travel in excess of 200 km have been recorded (Richardson and Reynolds, 2000).

The occurrence of the GLOF is mainly dependent on the behaviour of the glacial lakes and the surroundings over time due to the slope failure of the rock and ice. The geomorphology of the high Himalayan region is constantly changing so it is vital to monitor the glacial lakes and its surrounding over time in order to reduce the GLOF hazard. Glacial hazard assessment using remote sensing and satellite imagery has been effective for remote areas of Himalaya, and remediation techniques have been successfully developed in the different parts of the world including Peruvian Andes (Richardson and Reynolds, 2000). This research has developed the comprehensive "glacial lake vulnerability assessment framework" based on combined GIS techniques and remote sensing datasets that has been discussed in the previous chapter.

This research has analysed the glacial hazard management since 1980s around Himalaya region, Nepal and concluded that some of the initiatives to minimize the GLOF risk and climate change adaptation are more effective than others. Thus, this allowed to identify the facilitating and obstructing factors of GLOF hazard mitigation and climate change adaptation at the region. While these factors play an important role in GLOF hazard mitigation and climate change adaption other soft solutions including public awareness, social equality and political willingness are paramount. Thus, these adaptative strategies should be based on the new environmental changes and related hazard as well as socio-economical changes.

The next step is to build new adaptive strategies based on these factors to identify new and existing hazards and to reduce human vulnerability to glacier hazards over the long term. Local planning and long-term development agenda of the region should more focus on research and development initiatives to reduce exposure of the human-settlement towards GLOF. Important lessons should be learned from the Tsho Rolpa lake lowering project in terms of the early warning system. It needs to be simple to operate, easy to maintain, technically sound and reliable. The relocation of the people from the possible floodplain should only be considered if threat is imminent.

Chapter 7

Conclusions and Recommendations

This research aims to create a vulnerability assessment framework of the glacial lakes based on empirical evidence and remote sensing data sets to mitigate the GLOF hazard. This will help to understand the present conditions of the glacial lake in the region. In achieving this aim, the unique vulnerability assessment framework of the glacial lake is developed and validated by examining 21 PDGL's susceptibility towards GLOF. These lakes are listed by the government of Nepal and various research organisations (e.g., ICIMOD) as potentially dangerous at present. The proposed assessment framework also categorised most of these glacial lakes as dangerous or likely to break at any time. The characteristic of flood events and downstream impact assessment is also conducted while the GLOF formation mechanism is explored. The potential flood volume calculation (PFV) is also improved in the case of Himalayan glacial lakes. Due to its high altitude and difficult geographical conditions, the climate change adaptation and hazard mitigation strategies demand unique challenges. Based on empirical evidence, local traditional knowledge, and the use of modern technologies, this research also concluded the climate change adaptation and GLOF hazard mitigation strategies to build a more resilient and sustainable community. This research has improved the understanding of the GLOF hazard dynamic and effective mitigation measures in the Himalayan region Nepal and around the world with similar geographical conditions.

7.1 Conclusions

GLOF characteristic, vulnerability factor and conditions

A detailed investigation of the past GLOF events and downstream impact assessment is conducted to understand the GLOF hazard dynamics and hydrodynamic characteristics. It is necessary to understand these features to assess the vulnerability of these glacial lakes. HEC-RAS is used to determine the flood characteristics of the GLOF events in Tam Pokhari in 1998. All the recorded past events are analysed, and erosion and sedimentation in a downstream flood plain (U-shaped and V-shaped valley) is also discussed. Furthermore, based on empirical evidence, the lake volume and peak discharge calculation of the GLOF events are improved.

This research has identified, measured and modelled the glacial lake vulnerability factors that significantly contribute towards GLOF, including Mean Slope of the dam (S_D), Distance between the lake and glacier terminus (D), Slope between the lake and glacier terminus (S_L), Area of the lake (A_L), Area of the host glacier (A_G), Extreme weather; Rainfall (R) and Seismic events (S) based on combined AHP, QGIS and empirical evidence. By analysing these factors, the total vulnerability score (TVS) of the lake has been calculated. Specific criteria have been applied to select these variables. These factors should significantly impact the stability of the glacial lake and associated previous GLOF events. They should not be reproducible from each other and can be measured using medium resolution satellite data and GIS techniques.

Moreover, this investigation also concluded that the main GLOF is the triggering factor and conditions of the lake and its surroundings based on past events. There are three main triggering factors: one is considered complex and the other two as direct, and these are associated with four failure mechanisms. Time-effects are the complex triggering factor that led to moraine collapse and eventually catastrophic events. Seismic movement and extreme weather conditions are the direct cause of the GLOF, which has various adverse effects on the region and led to different failure mechanisms, including the increase in hydrostatic pressure on the lake overtopping surge wave and piping or seepage failure.

The following conclusion is drawn in terms of the hydrodynamic characteristics of the glacial lakes, their conditions and triggering factors from the historic GLOF events.

- The maximum peak discharge of the 1998 Tam Pokhari GLOF events was 9500 m^3/s, and the full breach formation time was about 45 minutes.

- During the GLOF, erosion and deposition took place recurrently as sediment deposited suddenly, the strong flow of the GLOF continued downstream, and caused more damage. The sediment appeared as means of transport for water, while sediment flow caused GLOF to be more distractive.

- There are various GLOF recorded within Nepal and the surrounding region since the 1960s, but 1985's Dig Tsho glacial lake outburst flood was the most devastating which destroyed the almost completed Namche Hydropower Plant (estimated loss of USD 1.5 million), 14 bridges, trails, agricultural land and also it was reported that many lives were lost.

- In the Himalayan region, narrow V-shaped valleys are dominant, created by river incisions at lower segments of the U-shaped valley. The downstream impact of the GLOF and characteristics of the flood flow are dominant in geological structures.

Measuring, modeling different variables and glacial lake vulnerability assessment framework

This research has identified the variable that has significantly contributed toward the GLOF has been categorized based on each other's prevalence and assigned their weight according to their importance with help from the AHP method. The values of these variables are further divided into four different percentiles, and the total score of the factor is calculated. Total vulnerability score (TVS) of any glacial lake can be calculated by adding the total score of all the factors. Maximum possible TVS of any lake can be 1(100%). To improve the reliability of the proposed vulnerability assessment framework, TVS is further divided into four different categories based on their likeliness of suffering GLOF. They are Low ($\text{TVS} = < 40\%$), Medium ($\text{TVS} = 41 - 50\%$), High ($\text{TVS} = 51 - 60\%$), Very High ($\text{TVS} < 61\%$). Based on this proposed vulnerability assessment framework, the vulnerability of eleven glacial lakes before the GLOF events was examined. The retrospective modelling of the glacial lake prior to the disaster was carried out. Furthermore, within those investigated glacial lakes, the vulnerability of six of them was categorised as very high, four of them are medium, and one categorises as low.

This tool can be used to assess the likeliness of the lake suffering the GLOF. Hence, this suggests that the effectiveness of the proposed vulnerability assessment framework is very high. This assessment tool saves time and resources to prioritise the glacial lake for further field investigation and close monitoring to reduce the GLOF hazards. Often the field investigation of these glacial lakes is very labour-intensive and challenging due to the remoteness of the locations and small window of opportunity around the year to assess the site due to weather conditions. This will help to mitigate GLOF hazards and improve community resilience.

TVR scores of PDGLs and climate change adaptation in the region

There are currently about 21 PDGL in Nepal established by various studies (HMD Nepal; ICIMOD, 2011). This study found that the total vulnerability score (TVS) of seven out of 21 glacial lakes is very high, while four glacial lake's vulnerability score was high. The rest of the glacial lakes score was divided into medium and low equally, five each. Hence, the reliability of this proposed assessment framework is very high. As recommended, these glacial lakes and surroundings should be continuously monitored to mitigate the GLOF hazard in the region.

Additionally, this research concluded that the natural hazard mitigation and climate change adaptation is a complex process. This needs to be addressed at the policy level with advanced research and scientific investigations, emphasising the implementations by national, local and regional stakeholders. This research has analysed the glacial hazard management since the 1980s around the Himalayas region, Nepal and concluded that some of the initiatives to minimise the GLOF risk and climate change adaptation are more effective than others. Thus, this allowed us to identify the facilitating and obstructing factors of GLOF hazard mitigation and climate change adaptation in the region. While these factors are essential in GLOF hazard mitigation and climate change adaptation, other soft solutions, including public awareness, social equality, and political willingness, are paramount. Thus, these adaptive strategies should be based on the new environmental changes and related hazards and socio-economical changes.

Essential lessons should be learned from the Tsho Rolpa lake lowering project regarding the early warning system. It needs to be simple to operate, easy to maintain, technically sound and reliable. The relocation of the people from the possible floodplain should only be considered if the threat is imminent. The next step is to build new adaptive strategies based on these factors to identify new and existing hazards and to reduce human vulnerability to glacier hazards over the long term.

7.2 Recommendations

This research has investigated the historic GLOF events in the Himalayas region using remote sensing data sets, GIS techniques and the AHP method. Moreover, developed the vulnerability assessment framework to identify the susceptibility of the glacial lake towards GLOF by calculating the total vulnerability score (TVS). This can be applied to other glacial lakes in the Himalayan region. This assessment framework can conduct the qualitative outburst vulnerability assessment of the lakes in relatively limited time, cost and expertise. This assessment tool will help to reduce GLOF hazards in mountainous regions around the world.

The unique vulnerability assessment framework produced by this study can be used as a primary assessment tool to assess the likeliness of the GLOF occurrence in the region, which will help to prioritise the most vulnerable glacial lakes and take mitigation measures accordingly. This will possibly save many lives and expensive mountain infrastructure. Due to the complex nature of the glacial lake formation and glacial outburst flood (GLOF) triggering process, more research should be carried out in this area of research. Recommendations regarding future works to mitigate the GLOF hazard in the region and the current research project are:

- In the Himalayas region, the devastation caused by the past GLOF were not only caused by the water release from the lake but the associated debris flow and sediment transported by the flow. Hence, it is also necessary to monitor downstream floodplain and its geomorphology to mitigate the true extent of possible damage caused. In addition, the sediment distribution on the channel bed can be monitored because it is associated with potential debris flow.
- Further field investigation can be carried out to fully understand the dam collapsing mechanism (vertical breach enlargement on sidewall collapse) in a

moraine-dammed glacial lake and improving accurate prediction of sediment transport.

- Further investigation can be carried out to model the water-sediment flow using HCE-RAS hydraulic modelling and couple the result from water only flow to get the entire understanding of the GLOF characteristic in the Himalayan region (field data must be collected to get accurate results).
- Comprehensive GLOF risk assessment should be mandatory in GLOF-prone regions as part of the planning application process. As the glacial lake's geomorphology and surroundings are constantly evolving, the risk assessment should be up to date.

- Natural hazard mitigation and climate change adaptation is a complex process. The region's local planning and long-term development agenda should more focus on research and development, initiatives to reduce exposure of the human settlement towards GLOF and improved communication and involvement of the local people.

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Appendix

A. HEC-RAS Modelling

Introduction

The hydraulic modeling is the application of fluid dynamic to simulate the movement of water. Hydraulic models are applied to determine the extent of a floodplain and probability of a flood occurrence.

By 2D hydraulic model, we can determine what would happen if, for instance, the dam failed and given that information how far the extent of the flood inundation goes, how fast the floodwave propagates, thus we can prepare evacuation maps, emergency action plans, etc. On the other hand, the 1D models, cannot determine the direction of flow, where the floodwave goes, and this is based upon the engineers judgment to address these unknowns. The 1D models can be useful in domains having confined corridors, steep valleys, etc., while 2D models are considered to be more practical in flat terrain, highly urbanized area where floodwave flowing around the buildings and through roads in various directions.

2D hydraulic models have been around for over 15-20 years, however, the real problems that consulting firms and municipalities have not been using the 2D modeling software were due to difficulties of setting up the 2D models and lack of required information, e.g. terrain models, landcover variation, etc., while setting up the model.

HEC-RAS 2D software developed by Hydrologic Engineering Center of U.S. Army Corps of Engineer is an free advanced two-dimensional flow simulator and hydraulic analyst where allows user to perform 2D and combined 1D/2D unsteady flow routing.

The 2D flow simulation by HEC-RAS 2D can be performed in number of ways. The following are examples:

- Detailed 2D channel modeling
- Detailed 2D channel and floodplain modeling
- Combined 1D channels with 2D floodplain areas
- Combined 1D channels/floodplains with 2D flow areas behind levees
- Directly connect 1D reaches into and out of 2D flow areas
- Directly connect a 2D flow area to 1D Storage Area with a hydraulic structure
- Multiple 2D flow areas in the same geometry
- Directly connect multiple 2D flow areas with hydraulic structures
- Simplified to very detailed Dam Breach analyses
- Simplified to very detailed Levee Breach analyses
- Mixed flow regime. The 2D capability (as well as the 1D) can handle supercritical and subcritical flow, as well as the flow transitions from subcritical to super critical and super critical to subcritical (hydraulic jumps).

Objectives of This Workshop

1. Introduction to HEC-RAS 2D and two dimensional modeling advantages relative to 1D models

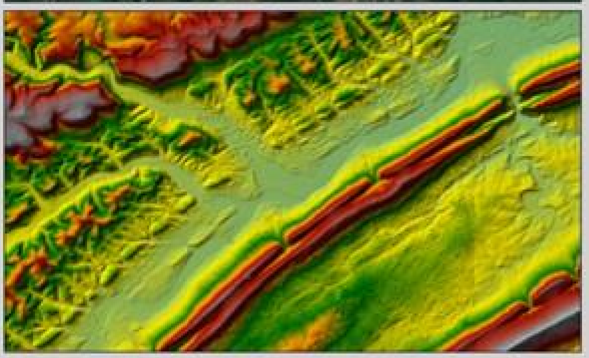
2. Required geophysical and flow information for setting up HEC-RAS 2D models

3. Overview of how to set-up a combined 1D/2D unsteady flow model in HEC-RAS

4. Overview of how to execute a combined 1D/2D unsteady flow model in HEC-RAS

5. Overview of how to demonstrate the result of a combined 1D/2D unsteady flow model in HEC-RAS and RAS Mapper output capabilities

Study Domain



Location:
Bald Eagle Creek, Pennsylvania

Existing Structures:
Dam, Levee, man-made and/or geophysical Obstructions

Required Operating Systems:
Windows XP, Vista, 7, 8, 8.1, and 10 both 32-bit and 64-bit

- HEC has added the ability to perform two-dimensional (2D) hydrodynamic routing within the unsteady flow analysis portion of HEC-RAS.

- Users can now perform one-dimensional (1D) unsteady-flow modeling, two-dimensional (2D) unsteady-flow modeling (Saint Venant equations or Diffusion Wave equations), as well as combined 1D and 2D unsteady-flow routing.

- 2D flow modeling is accomplished by adding 2D flow area elements into the model in the same manner as adding a storage area.

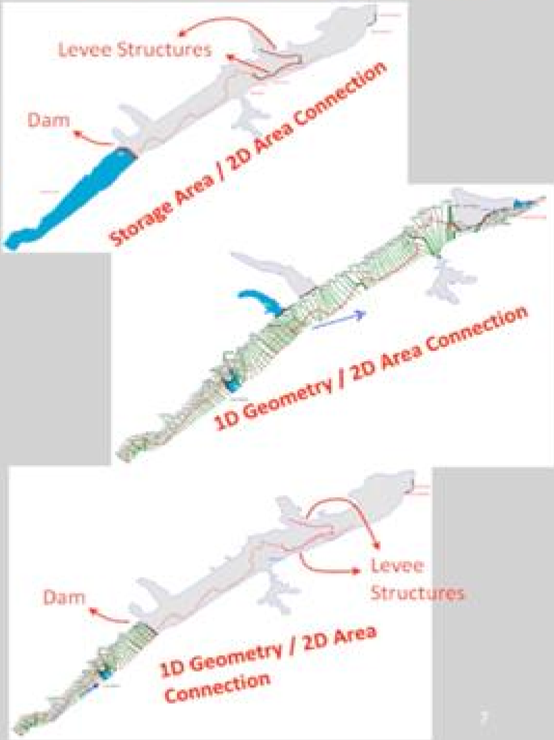
- A 2D flow area is added by drawing a 2D flow area polygon; developing the 2D computational mesh; then linking the 2D flow areas to 1D model elements and/or directly connecting boundary conditions to the 2D areas.

advantages relative to 1D models

- The 2D flow modeling algorithm in HEC-RAS has the following capabilities:

a) Can perform 1D, 2D, and combined 1D and 2D modeling.
b) Saint-Venant or Diffusion Wave Equations in 2D.
c) Implicit Finite Volume Solution Algorithm.
d) 1D and 2D Coupled Solution Algorithm.
e) Unstructured or Structured Computational Meshes.
f) Detailed Hydraulic Table Properties for 2D Computational Cells and Cell Faces.
g) Detailed Flood Mapping and Flood Animations.
h) Multi-Processor Based Solution Algorithm (Parallel Computing).
i) 64-Bit and 32-Bit Computational Engines.

Different Association of 1D - 2D Geometries



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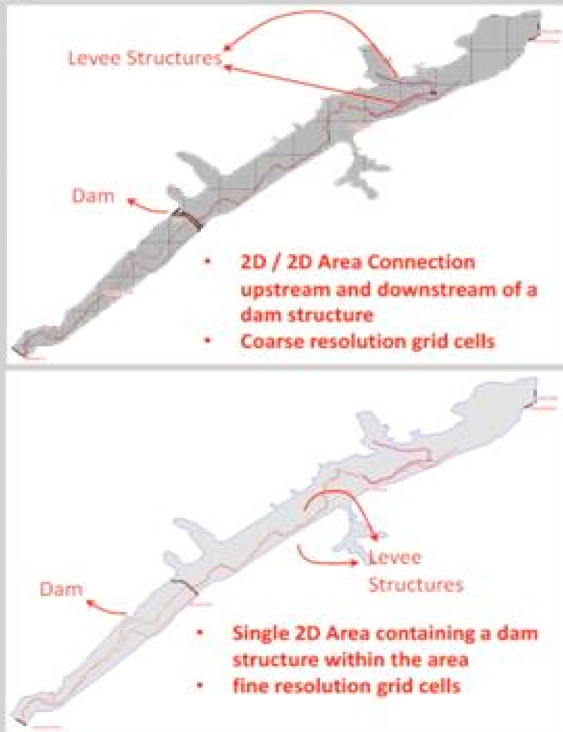

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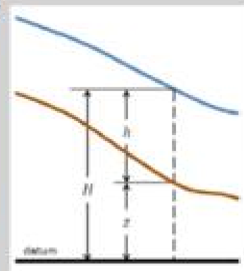


$H(x, y, t) = z(x, y) + h(x, y, t)$

z: bed elevation
h: water depth
H: water surface elevation
u , v : x , y velocities

g : gravi. accel. ; v_t : horz. Eddy. Coeff.
c_f : bed friction coeff. ; f : Coriolis par.

Full Saint-Venant (Dynamic Wave) equation:

$$\frac{\partial H}{\partial t} + \frac{\partial hu}{\partial x} + \frac{\partial hv}{\partial y} + q = 0 \quad \textit{continuity equ.}$$

Momentum equs.

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -g\frac{\partial H}{\partial x} + v_t\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) - c_f u + f v$$

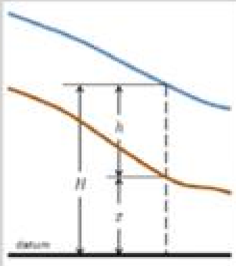
$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -g\frac{\partial H}{\partial x} + v_t\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) - c_f v + f v$$

advantages relative to 1D models

- The 2D flow modeling algorithm in HEC-RAS has the following capabilities:

a) Can perform 1D, 2D, and combined 1D and 2D modeling.
b) **Saint-Venant or Diffusion Wave Equations in 2D.**
c) Implicit Finite Volume Solution Algorithm.
d) 1D and 2D Coupled Solution Algorithm.
e) Unstructured or Structured Computational Meshes.
f) Detailed Hydraulic Table Properties for 2D Computational Cells and Cell Faces.
g) Detailed Flood Mapping and Flood Animations.
h) Multi-Processor Based Solution Algorithm (Parallel Computing).
i) 64-Bit and 32-Bit Computational Engines.

Unsteady, advection, turbulence, and Coriolis Terms can be disregarded to arrived at simplified form



$H(x,y,t) = z(x,y) + h(x,y,t)$

z: bed elevation
h: water depth
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$$\frac{\partial H}{\partial t} + \frac{\partial hu}{\partial x} + \frac{\partial hv}{\partial y} + q = 0 \quad \textit{continuity equ.}$$

Momentum equs.

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -g\frac{\partial H}{\partial x} + v_t\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) - c_f u + f v$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -g\frac{\partial H}{\partial x} + v_t\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) - c_f v + f v$$

advantages relative to 1D models

- The 2D flow modeling algorithm in HEC-RAS has the following capabilities:

a) Can perform 1D, 2D, and combined 1D and 2D modeling.
b) **Saint-Venant or Diffusion Wave Equations in 2D.**
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g) Detailed Flood Mapping and Flood Animations.
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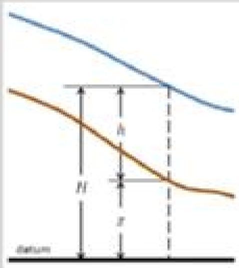

$H(x,y,t) = z(x,y) + h(x,y,t)$

z: bed elevation
h: water depth
H: water surface elevation
u , v : x , y velocities

g : gravi. accel. ; v_t : horz. Eddy. Coeff.
c_f : bed friction coeff. ; f : Coriolis par.

Diffusion Wave equation:

$$\frac{\partial H}{\partial t} + \frac{\partial hu}{\partial x} + \frac{\partial hv}{\partial y} + q = 0 \quad \textit{continuity equ.}$$

Momentum equs.

$$g\frac{\partial H}{\partial x} + g(S_x - S_f) = 0$$

$$g\frac{\partial H}{\partial y} + g(S_y - S_f) = 0$$

$$S_x = \frac{dz}{dx} ; S_y = \frac{dz}{dy} ; S_f = \frac{\tau}{\rho g R}$$

advantages relative to 1D models

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- The implicit solution algorithm allows for larger computational time steps than explicit methods.
- The Finite Volume Method provides an increment of improved stability and robustness over traditional finite difference and finite element techniques.
- 2D flow areas can start completely dry, and handle a sudden rush of water into the area.
- Additionally, the algorithm can handle subcritical, supercritical, and mixed flow regimes.

12

advantages relative to 1D models

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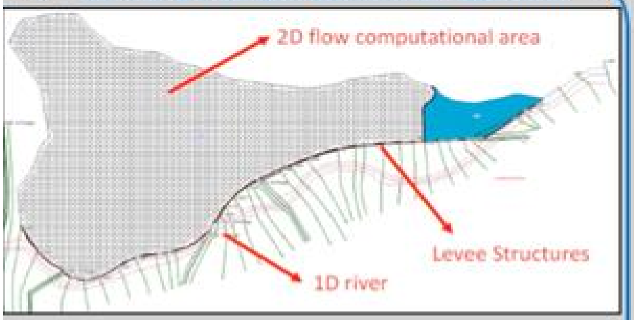

- The 1D and 2D solution algorithms are tightly coupled on a time step by time step basis with an option to iterate between 1D and 2D flow transfers within a time step.
- For Instance, consider a river that is modeled in 1D with the area behind a **levee** is modeled in 2D (connected hydraulically with a Lateral Structure). Flow over the **levee** (Lateral Structure) and/or through any **levee** breach is computed with a headwater from the 1D river and a tailwater from the 2D flow area to which it is connected. The weir equation is used to compute flow over the levee and through the breach.

13

advantages relative to 1D models

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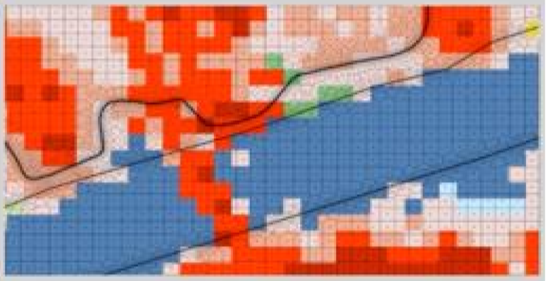
- The software was designed to use unstructured computational meshes, but can also handle structured meshes.
- This means that computational cells can be triangles, squares, rectangles, or even five and six- sided elements (the model is limited to elements with up to eight sides). The computational mesh does not need to be orthogonal but if the mesh is orthogonal the numerical discretization is simplified and more efficient.



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- Within HEC-RAS, computational cells do not have to have a flat bottom, and cell faces/edges do not have to be a straight line, with a single elevation.
- Instead, each Computational cell and cell face is based on the details of the underlying terrain.
- HEC-RAS has a 2D flow area pre-processor that processes the cells and cell faces into detailed hydraulic property tables based on the underlying terrain used in the modeling process.
- This type of model is often referred to in the literature as a "high resolution subgrid model" (Casulli, 2008).

advantages relative to 1D models

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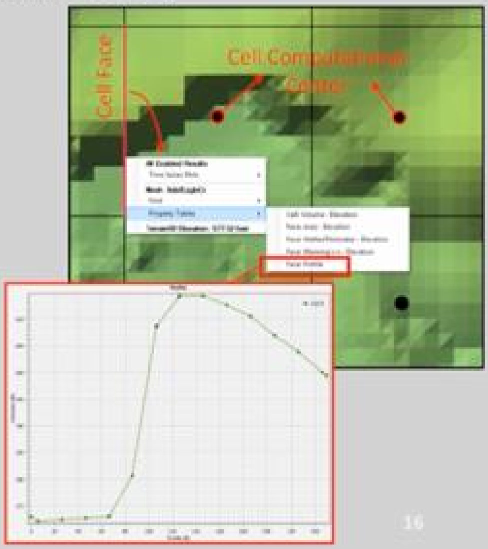
- For an example, consider a model built from a detailed terrain model (2ft grid-cell resolution) with a computation cell size of 200x200 ft. The 2D flow area pre-processor computes an elevation-volume relationship, based on the detailed terrain data (2ft grid), within each cell.



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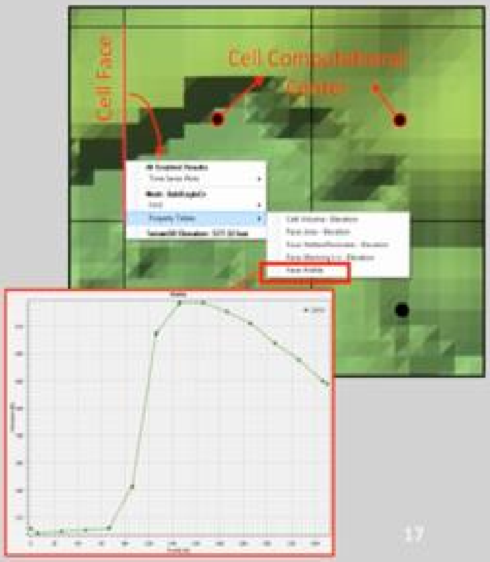
- The cell computational centers are the locations where the water surface elevation is computed for each cell.
- Each cell face is a detailed cross section based on the underlying terrain below the line that represents the cell face.



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- A cell can be partially wet with the correct water volume for the given water surface elevation (WSEL).
- Each computational cell face is evaluated similar to a cross section and is pre-processed into detailed hydraulic property tables (elevation versus - wetted perimeter, area, roughness, etc...).
- The flow moving across the face (between cells) is based on this detailed data.
- A small channel that cuts through a cell, and is much smaller than the cell size, is still represented by the cell's elevation volume relationship, and the hydraulic properties of the cell faces.
- Additionally, the placement of cell faces along the top of controlling terrain features (roads, high ground, walls, etc...) can further improve the hydraulic calculations using fewer cells overall. (application of ***breakline***)

18

1. Introduction to HEC-RAS 2D and two dimensional modeling advantages relative to 1D models

- The 2D flow modeling algorithm in HEC-RAS has the following capabilities:

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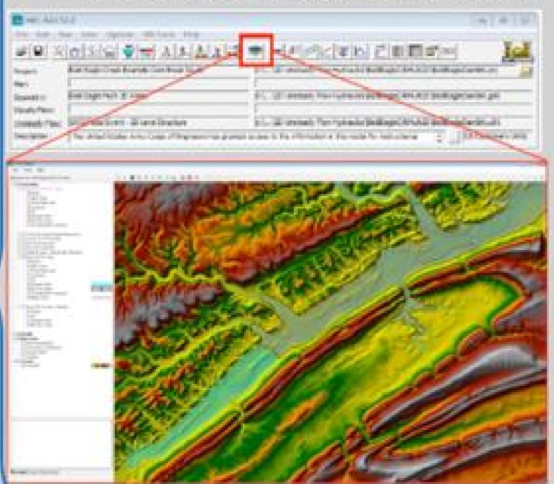
- Mapping of the inundated area, as well as animations of the flooding can be done inside of HEC-RAS using the RAS Mapper features.

- The mapping of the 2D flow areas is based on the detailed underlying terrain.



19

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- The 2D flow area computational solution has been programmed to take advantage of multiple processors on a computer (referred to as parallelization), allowing it to run much faster than on a single processor.

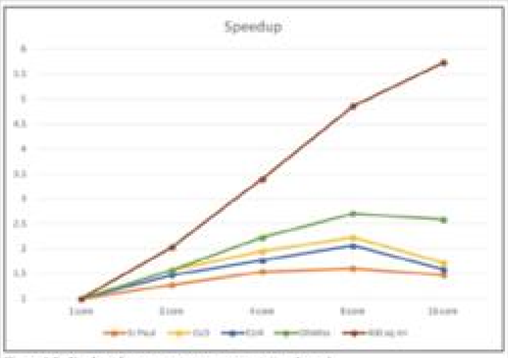

Figure 4-3. Number of processor cores vs. computational speed.

20

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- The 2D flow area computational solution has been programmed to take advantage of multiple processors on a computer (referred to as parallelization), allowing it to run much faster than on a single processor.

- 2D model made over larger area
- 2D model having the most geometrical details and specifications

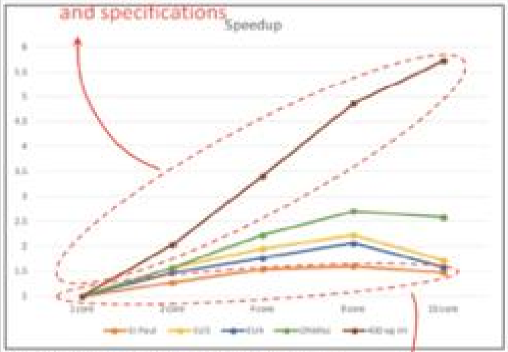

Figure 4-3. Number of processor cores vs. computational speed.

- 2D model made over smaler area
- 2D model having the least geometrical details and specifications

21

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i) **64-Bit and 32-Bit Computational Engines.**

- HEC-RAS now comes with both 64 bit and 32-bit computational engines. The software will use the 64-bit computational engines automatically if installed on a 64-bit operating system.
- The 64-bit computational engines run faster than the 32-bit and can handle much larger data sets.

22

Objectives of This Workshop

1. Introduction to HEC-RAS 2D and two dimensional modeling advantages relative to 1D models
2. **Required geophysical and flow information for setting up HEC-RAS 2D models**
3. Overview of how to set-up a combined 1D/2D unsteady flow model in HEC-RAS
4. Overview of how to execute a combined 1D/2D unsteady flow model in HEC-RAS
5. Overview of how to demonstrate the result of a combined 1D/2D unsteady flow model in HEC-RAS and RAS Mapper output capabilities

23

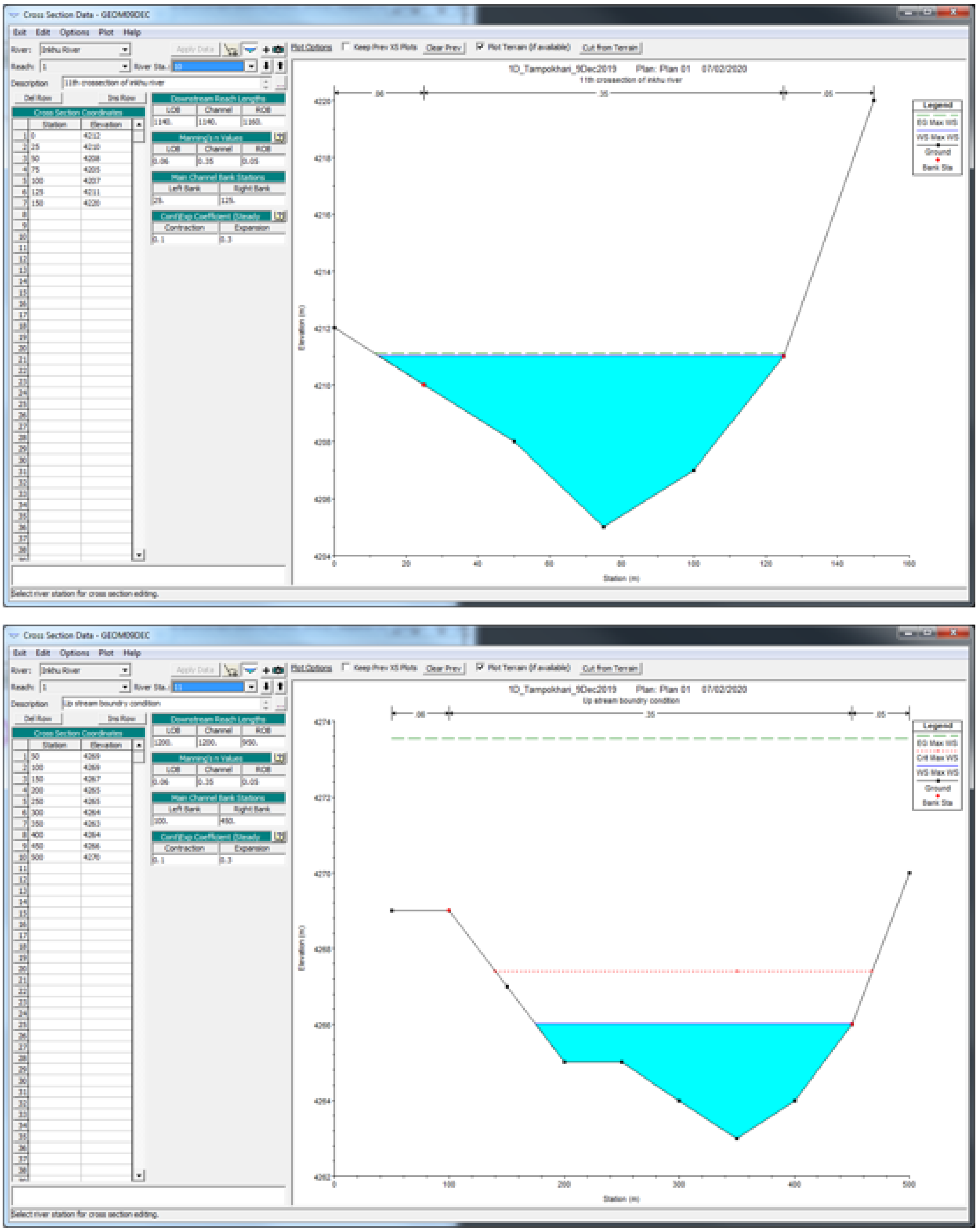
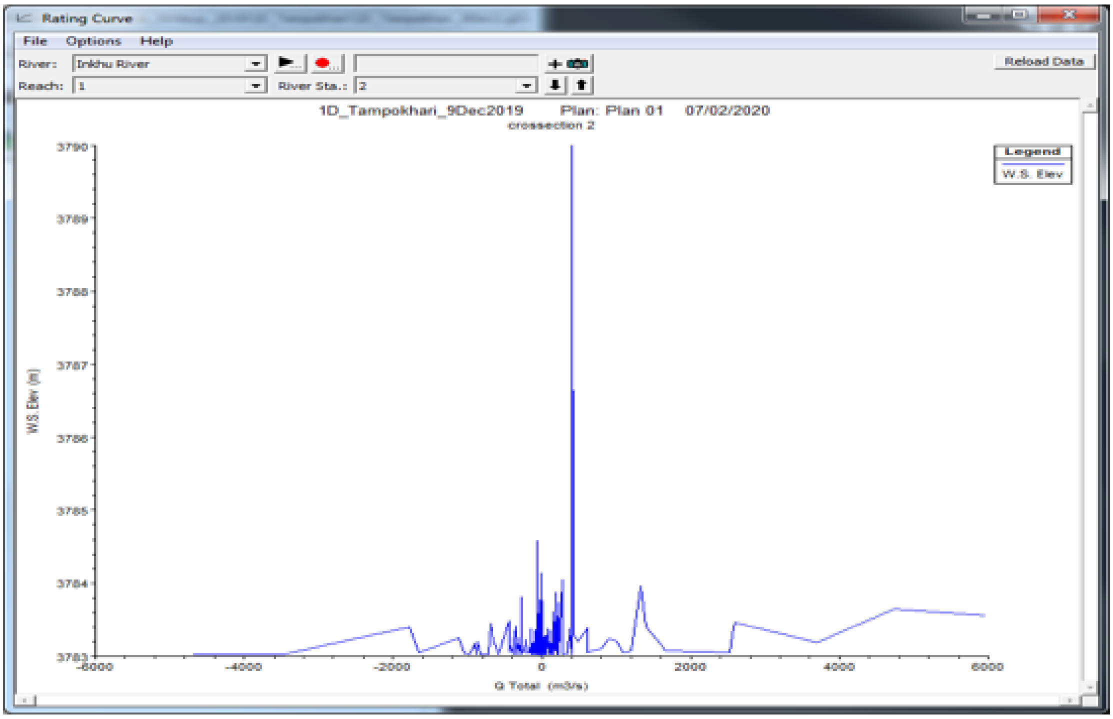


Figure A1 Water surface modelling



Cross Section Output

File Type Options Help

River: Inkhu River Profile: Max WS

Reach 1 RS: 0 Plan: Plan 01

Plan: Plan 01 Inkhu River 1 RS: 0 Profile: Max WS

		Element	Left OB	Channel	Right OB
E.G. Elev (m)	3724.78	Element	Left OB	Channel	Right OB
Vel Head (m)	0.05	Wt. n-Val.		0.350	0.050
W.S. Elev (m)	3724.74	Reach Len. (m)			
Crit W.S. (m)	3713.94	Flow Area (m2)		1416.85	361.80
E.G. Slope (m/m)	0.000331	Area (m2)		1416.85	361.80
Q Total (m3/s)	820.85	Flow (m3/s)		359.34	461.51
Top Width (m)	175.00	Top Width (m)		125.00	50.00
Vel Total (m/s)	0.46	Avg. Vel. (m/s)		0.25	1.28
Max Chl Dpth (m)	13.73	Hydr. Depth (m)		11.33	7.24
Conv. Total (m3/s)	45110.2	Conv. (m3/s)		19747.7	25362.5
Length Wtd. (m)		Wetted Per. (m)		131.50	55.13
Min Ch El (m)	3711.00	Shear (N/m2)		34.99	21.31
Alpha	4.43	Stream Power (N/m s)		8.87	27.18
Frctn Loss (m)		Cum Volume (1000 m3)			
C & E Loss (m)		Cum SA (1000 m2)			

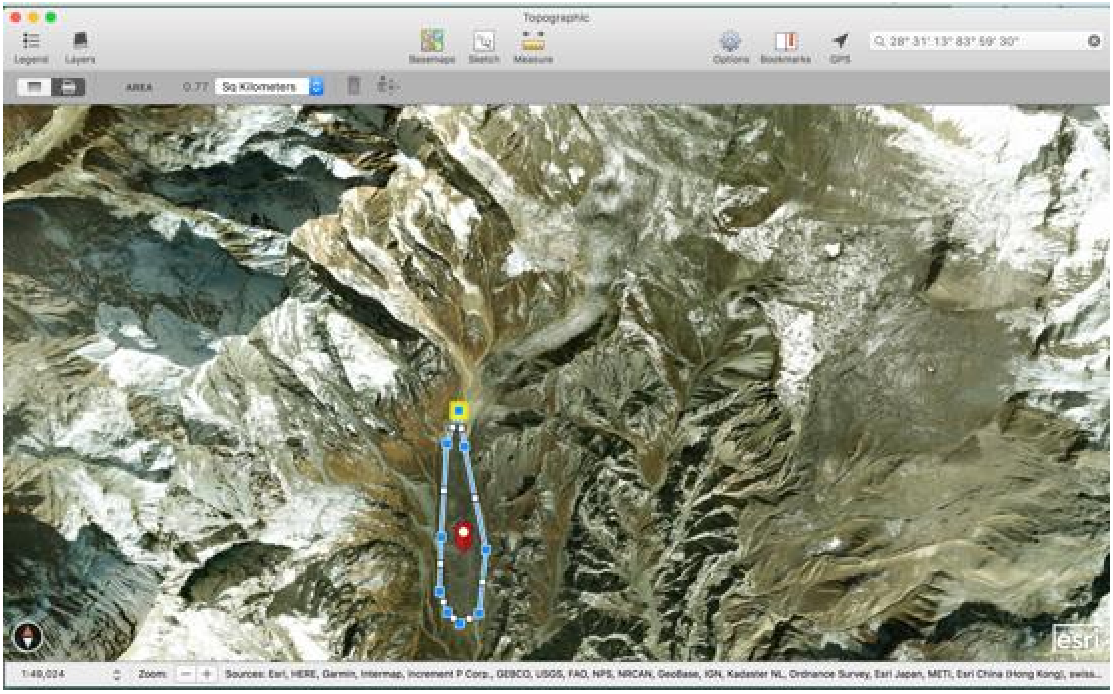
Errors, Warnings and Notes

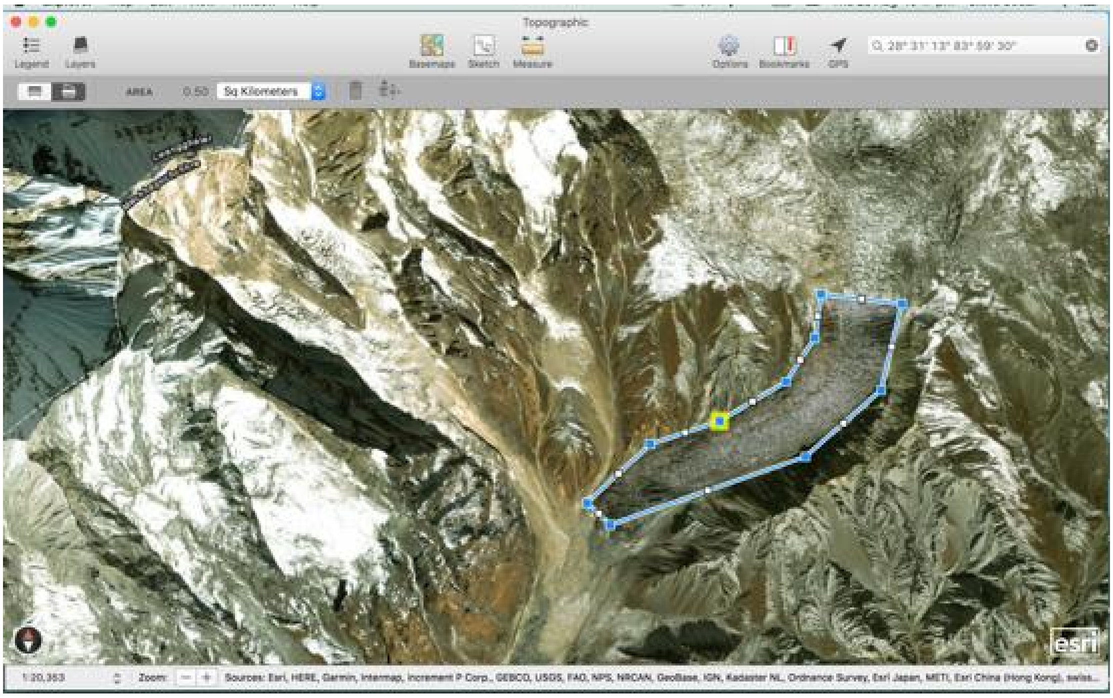
Select River Station

Figure A2 Cross Section Output

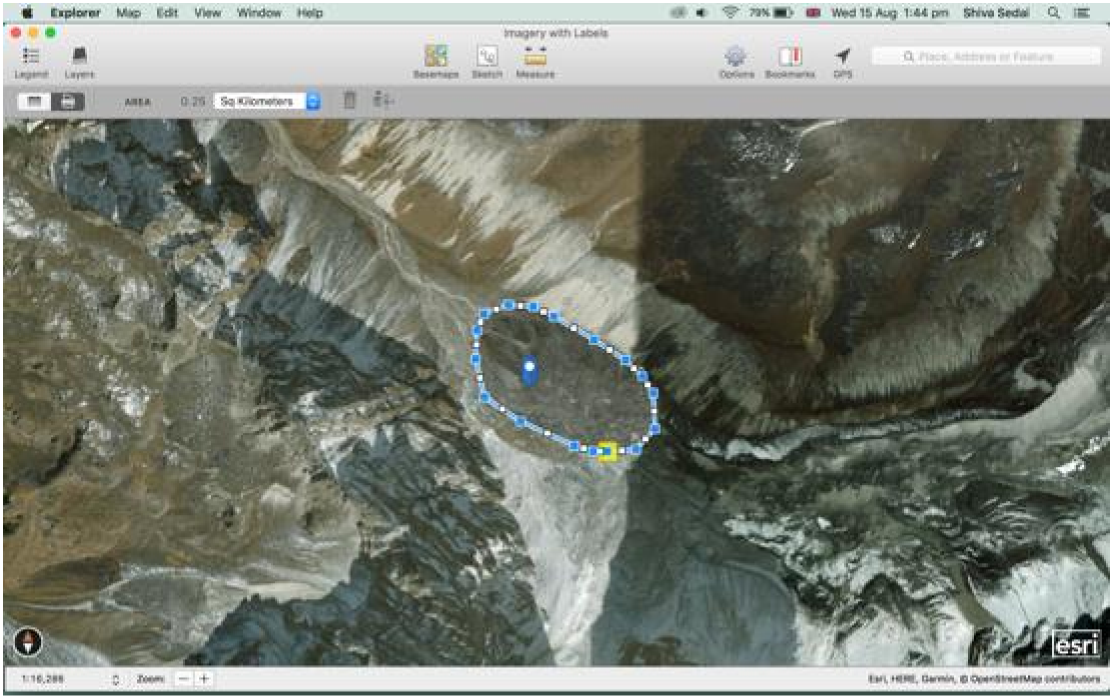
B. Area of the glacial lake and host glacier measurement

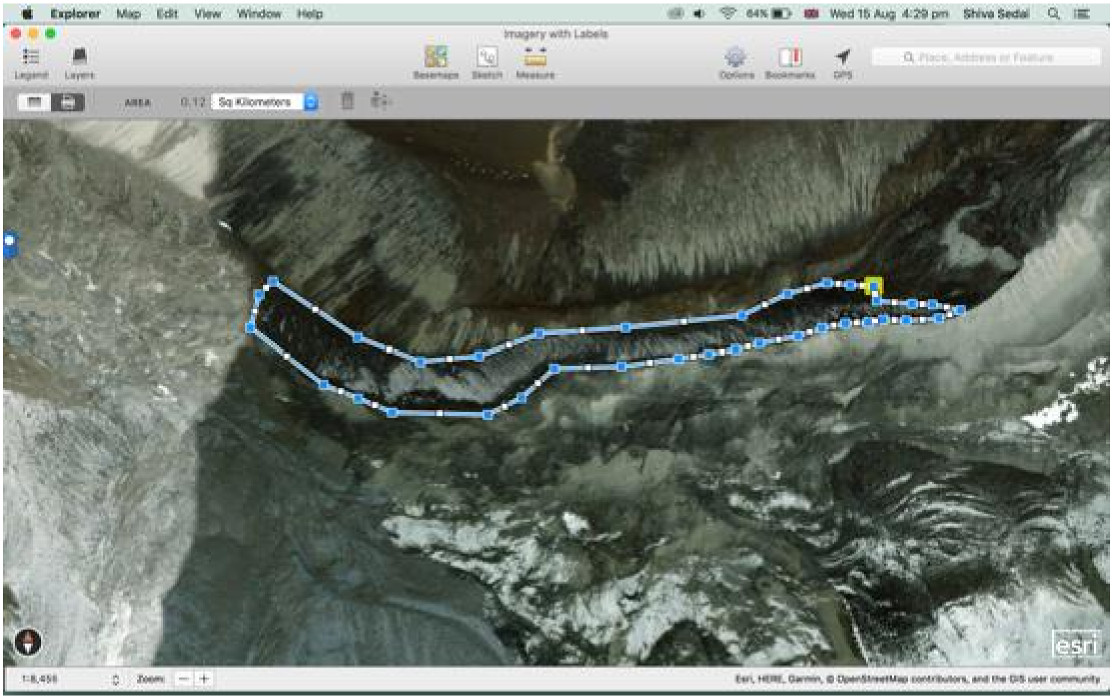
1. Seti Khola, Machhapuchhare, 450 years ago (28° 31’ 13” 83° 59’ 30”)



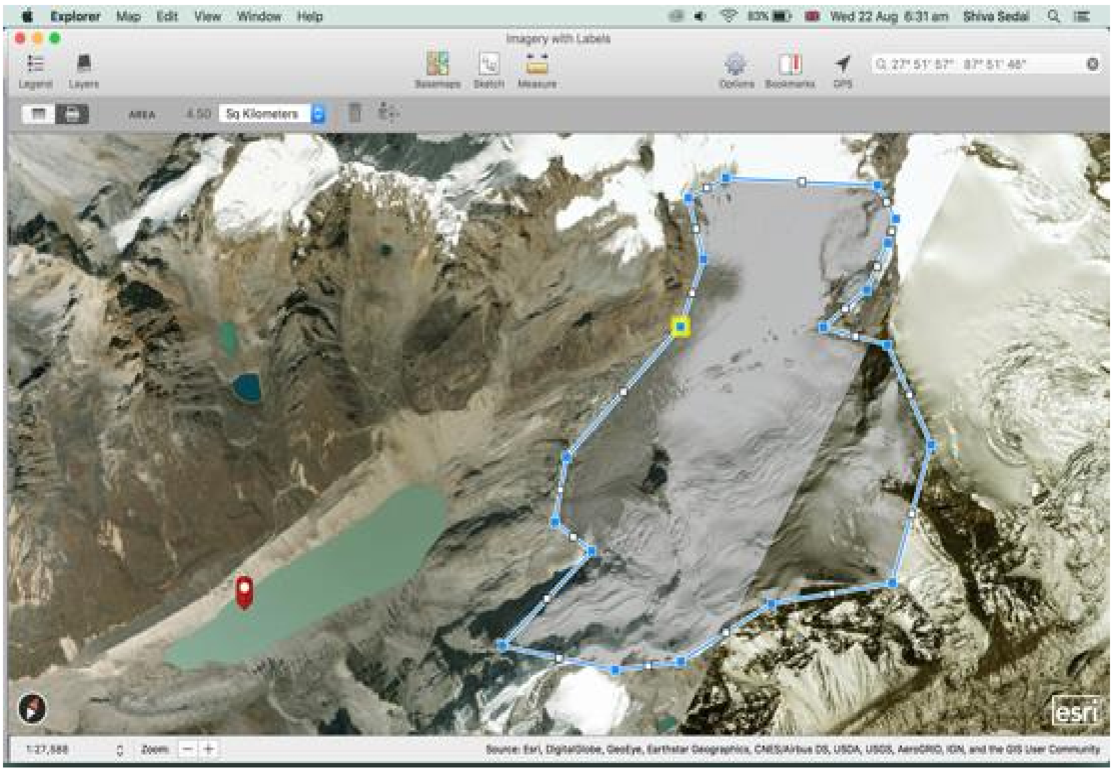


2. Dudh Koshi basin, Nare lake, Nepal*3 Sep 1977, (27° 49’ 47” 86° 50’ 12”)

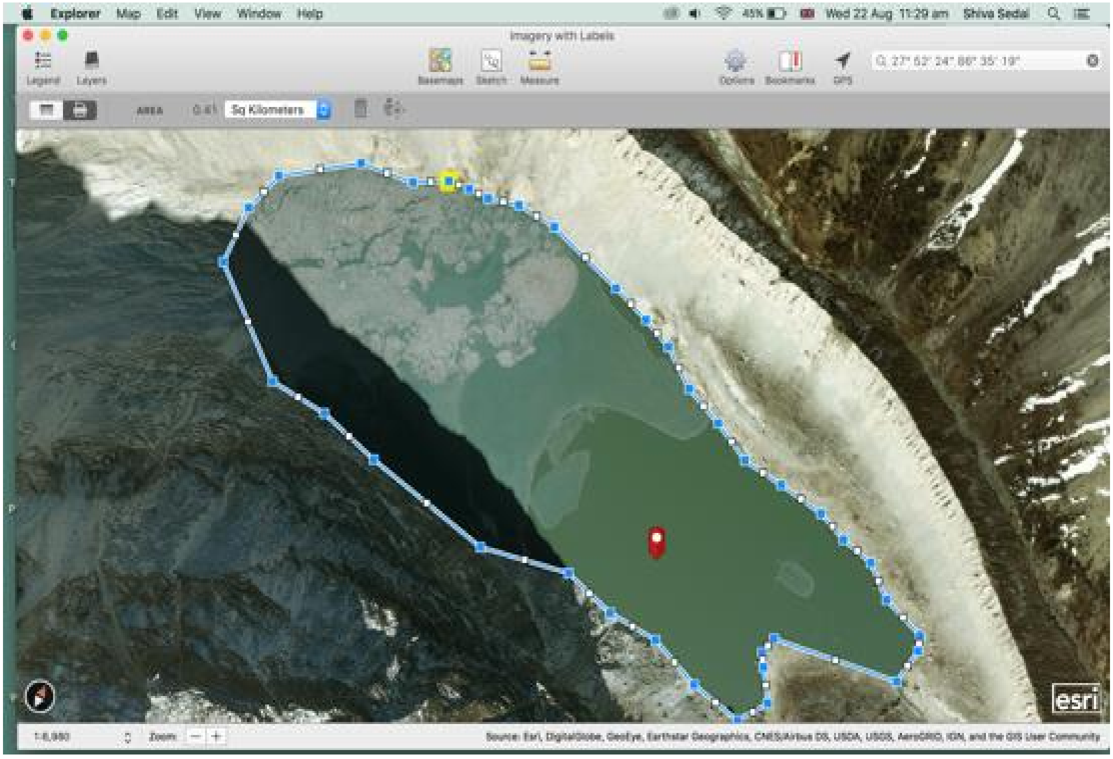


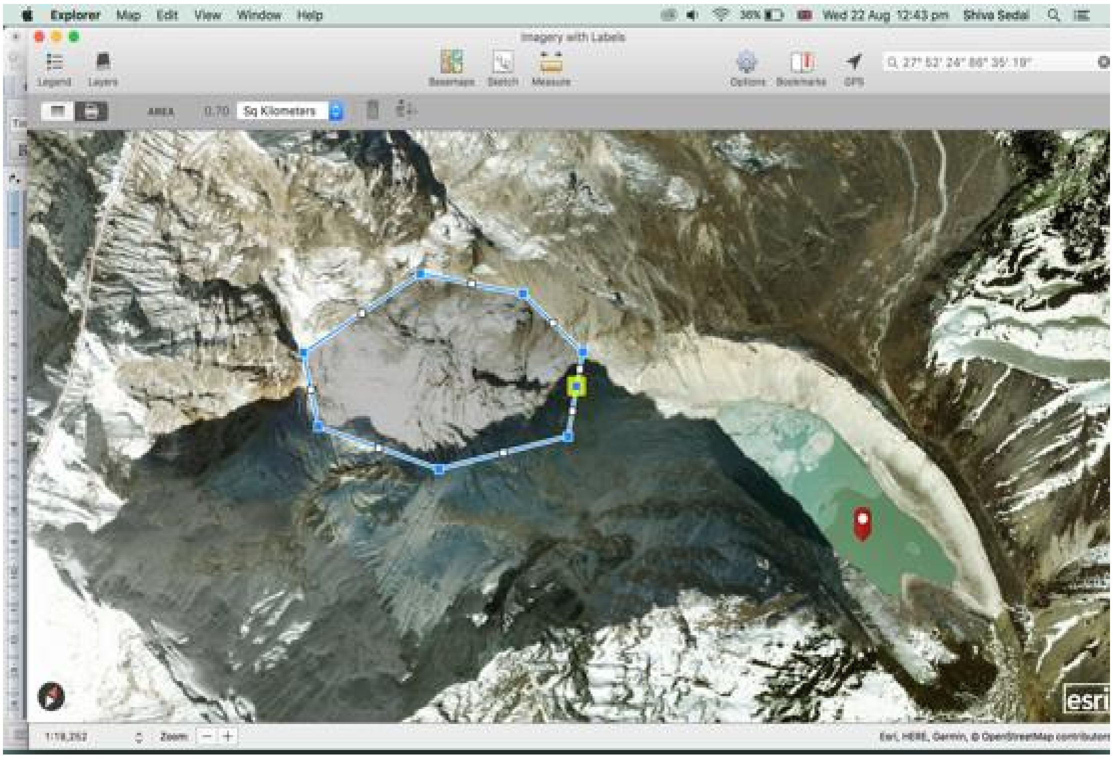


3.Tamor basin, Nagma Pokhari, 23 Jun 80 (27° 51’ 57” 87° 51’ 46”)

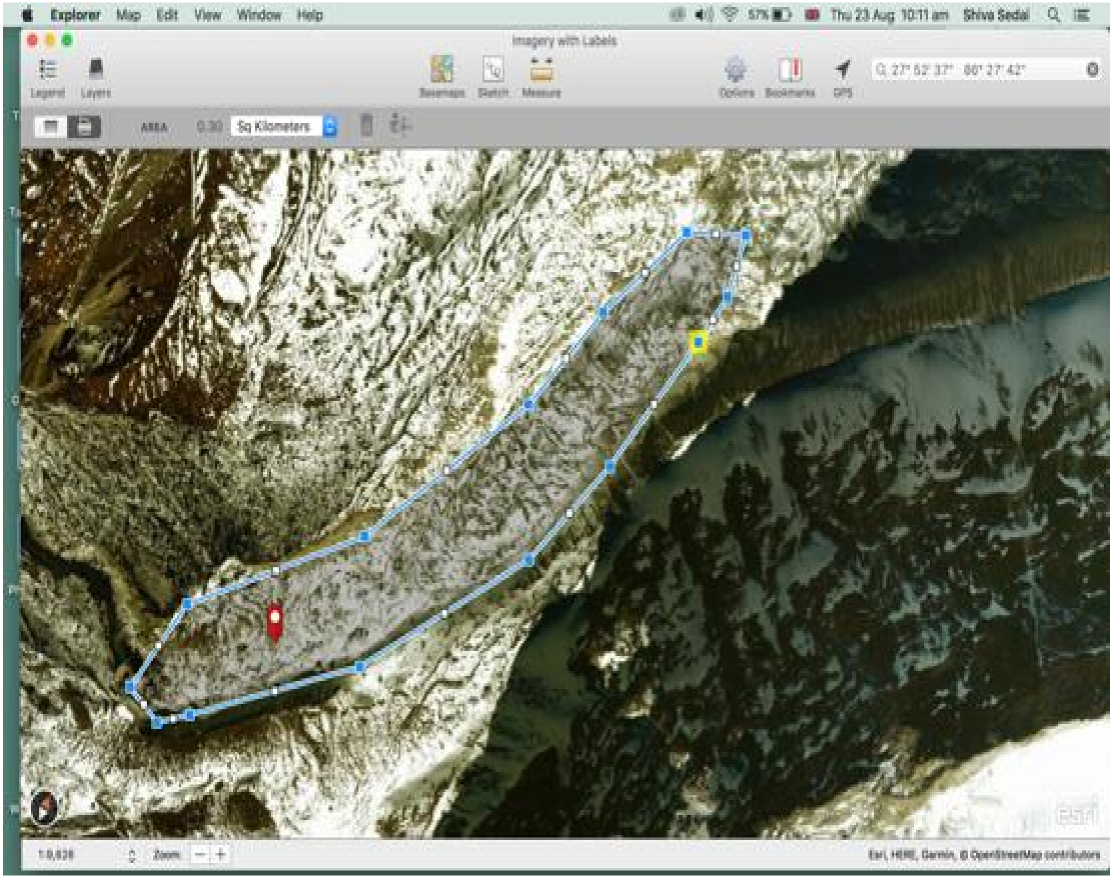


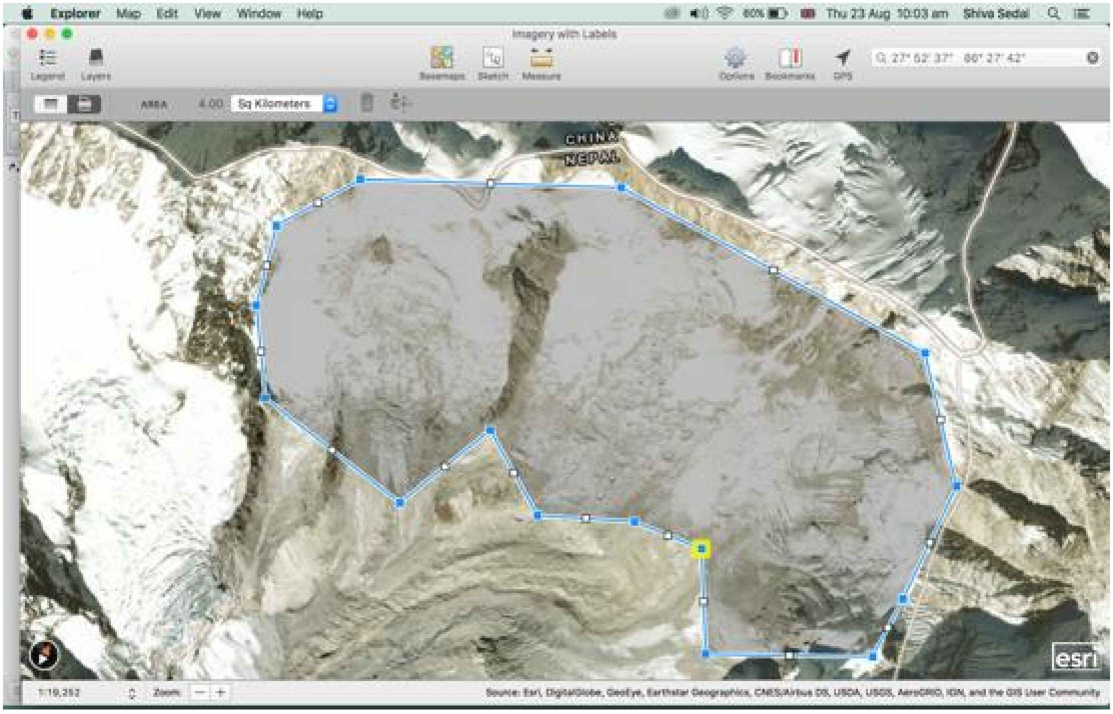
<u>4. Dudh Koshi basins, Dig Tsho, Nepal (27° 52’ 24″ 86° 35’ 19″)</u>



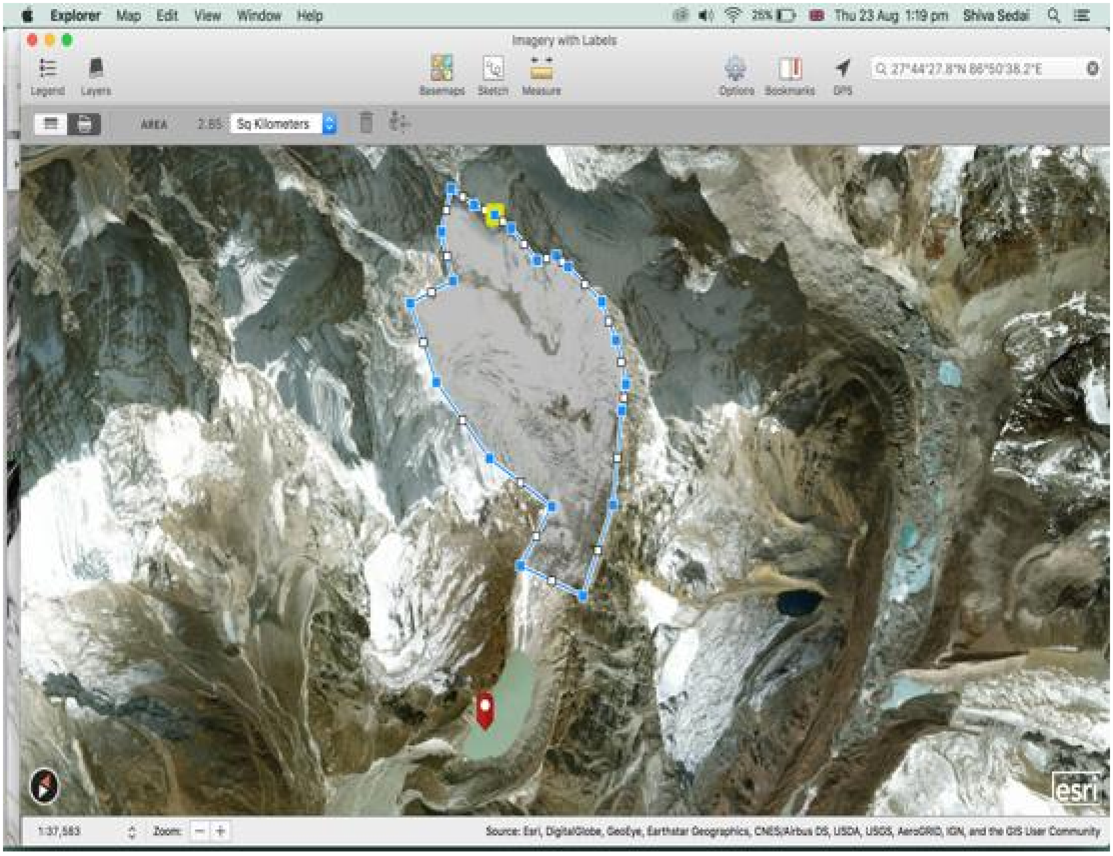


5.Tama Koshi basin, Chubung Tsho 12 Jul 91 (27° 52' 37" 86° 27' 42")

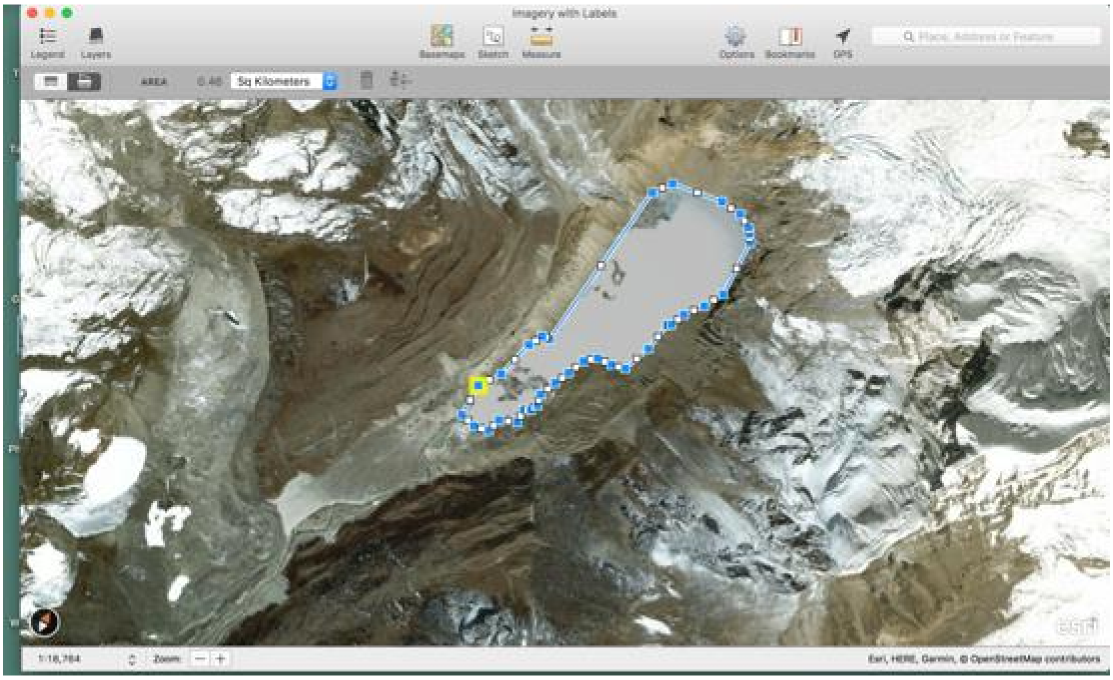


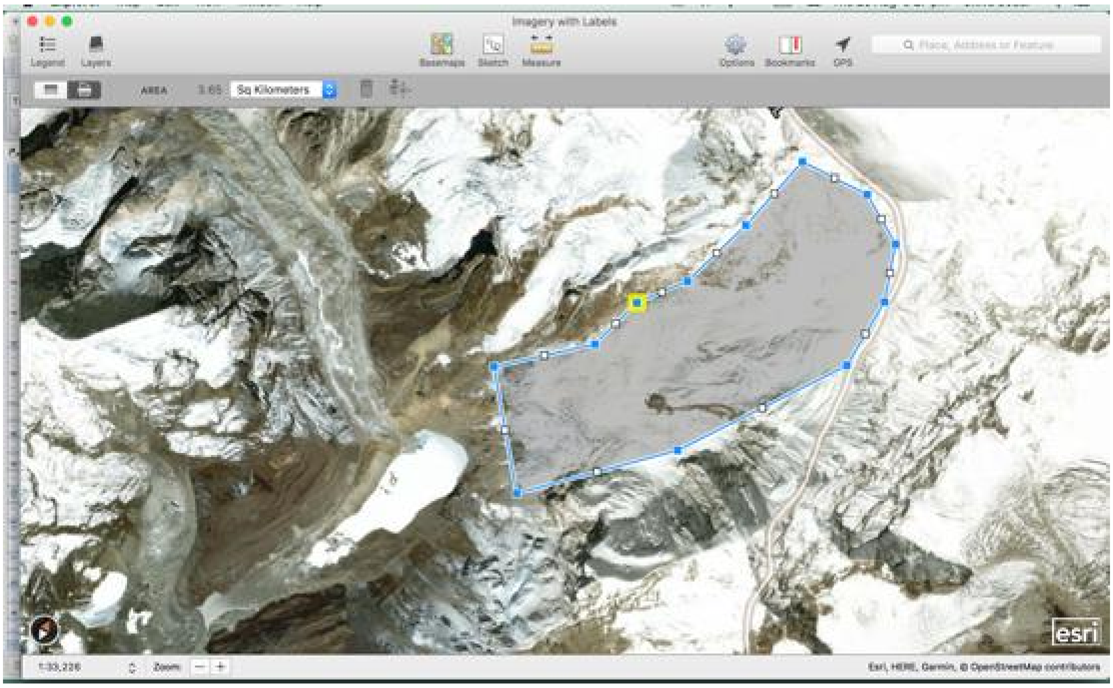


6. Dudh Koshi Basin, Tam Pokhari Tsho, 3 Sep 98 (27° 44’ 20” 86° 50’ 45”)

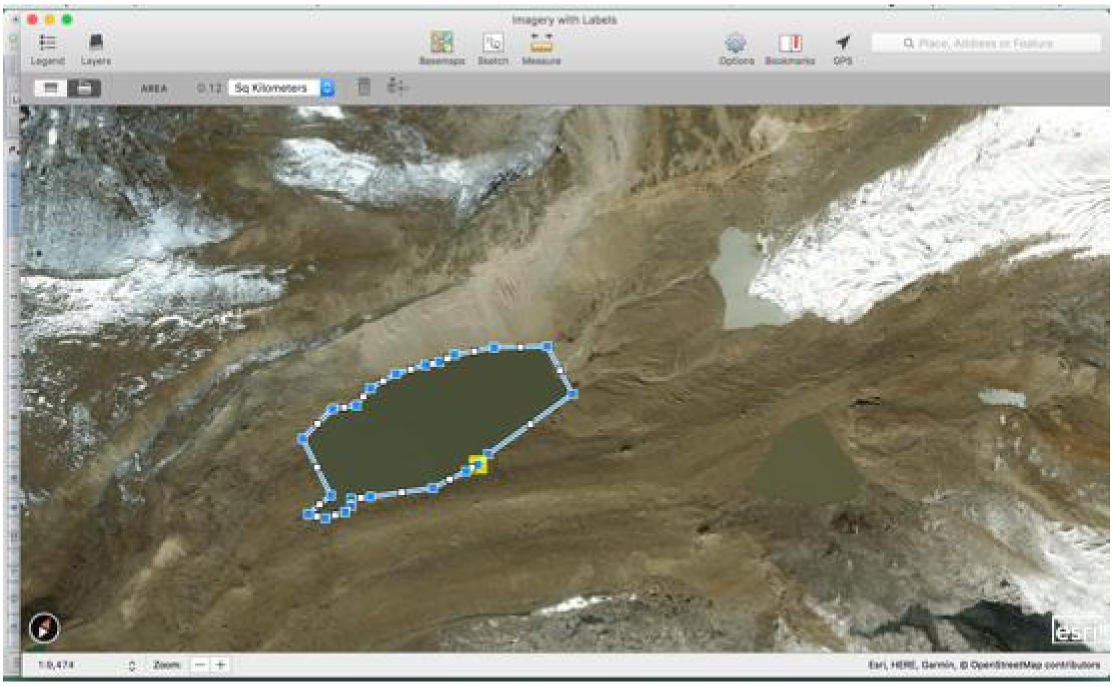


<u>**7. Arun River basin, Barun Khola, date; unknown (27° 50’ 33” 87° 05’ 01”)**</u>

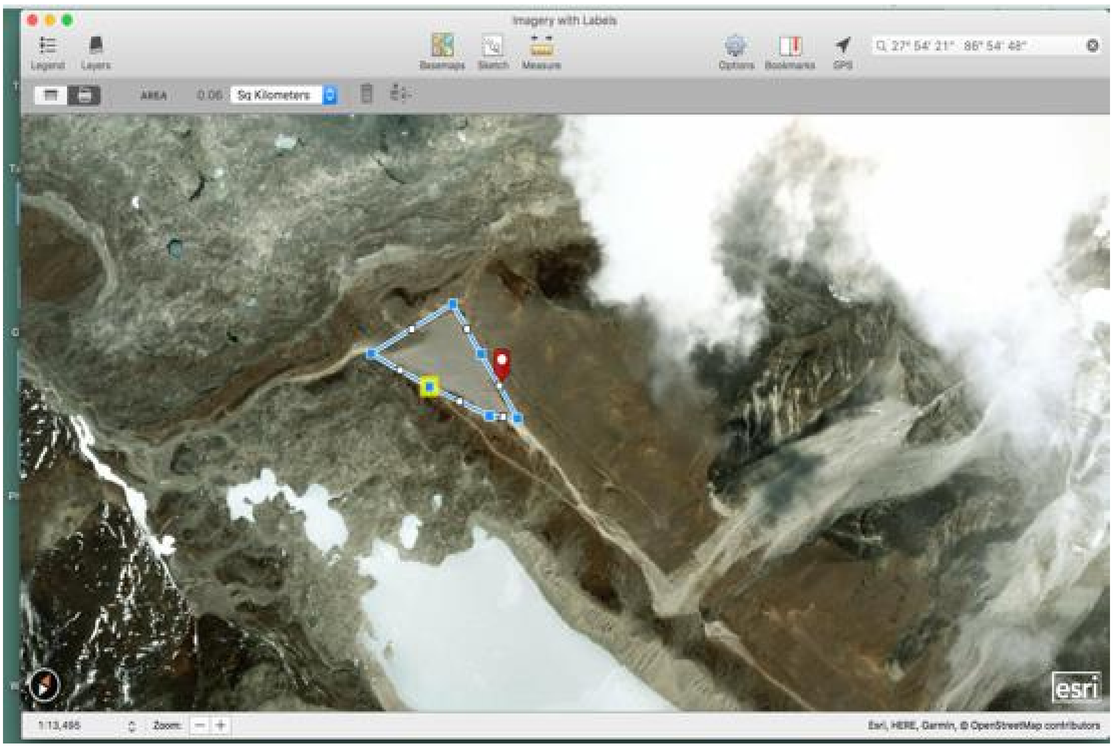


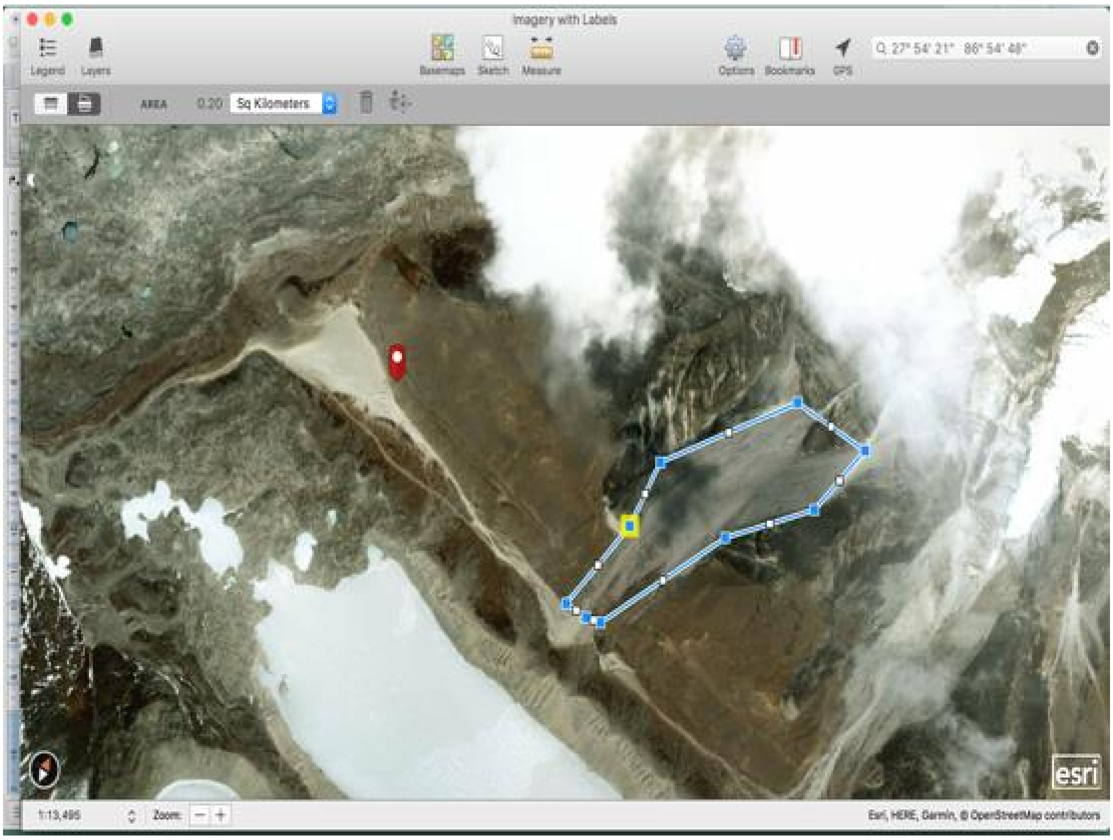


<u>8. Arun River basin, Barun Khola 01, date; unknown (27° 49’ 46”   87° 05’ 42”)</u>

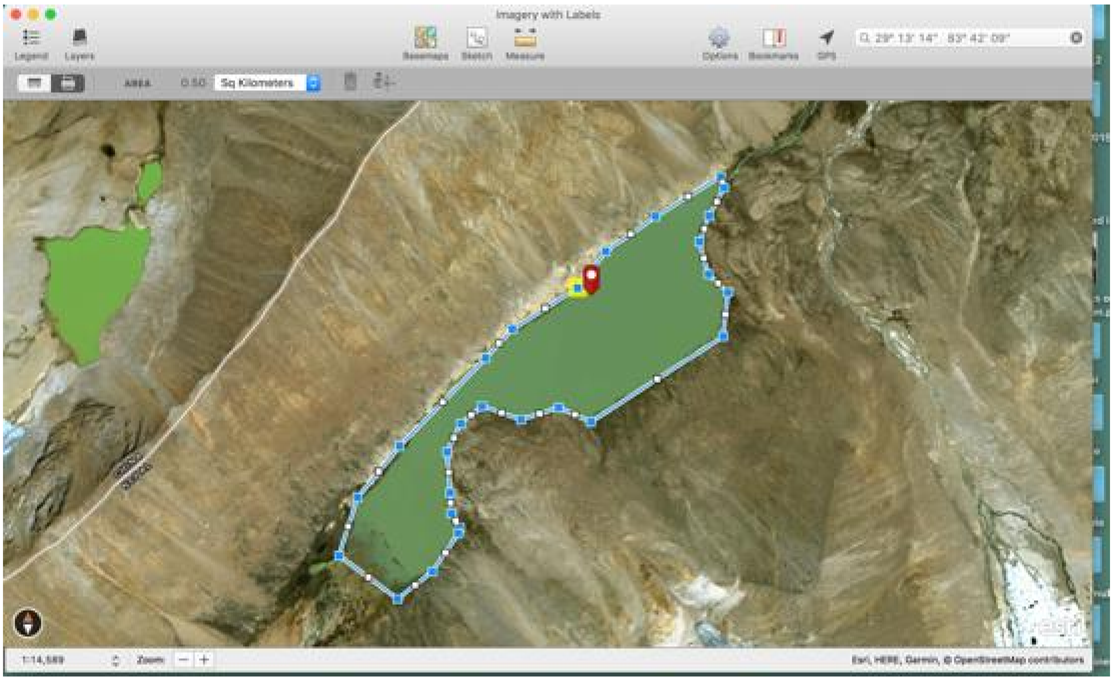


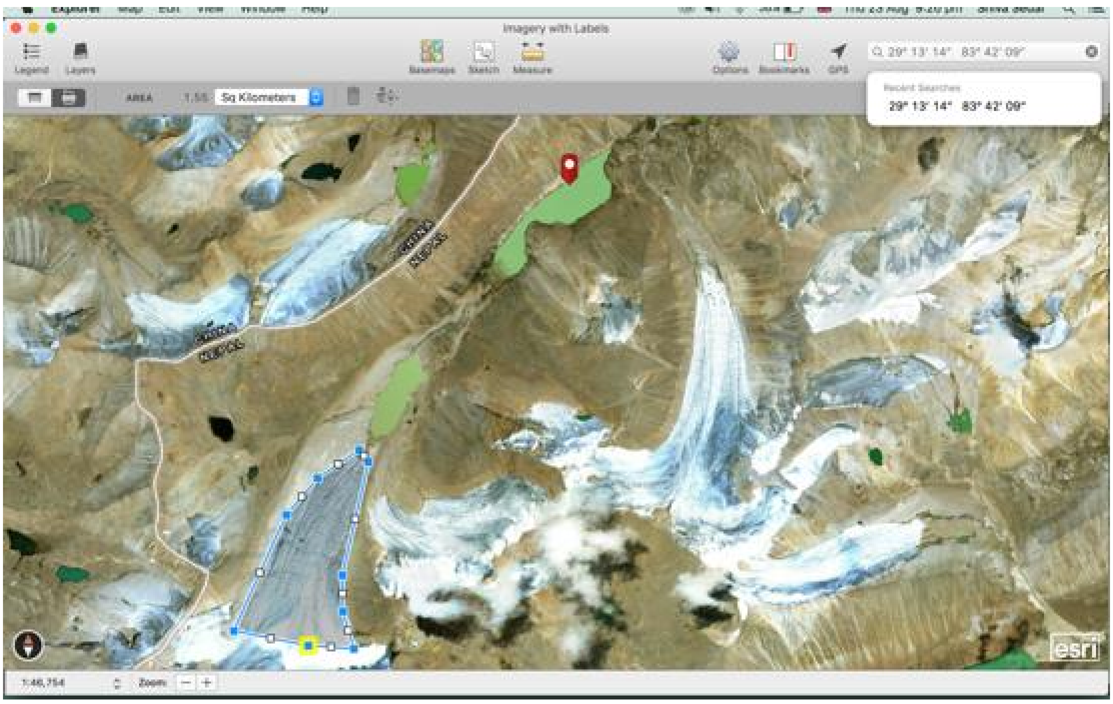
9. Dudh Koshi Basin, Chokarma Cho *   Unknown, (27° 54' 21" 86° 54' 48")



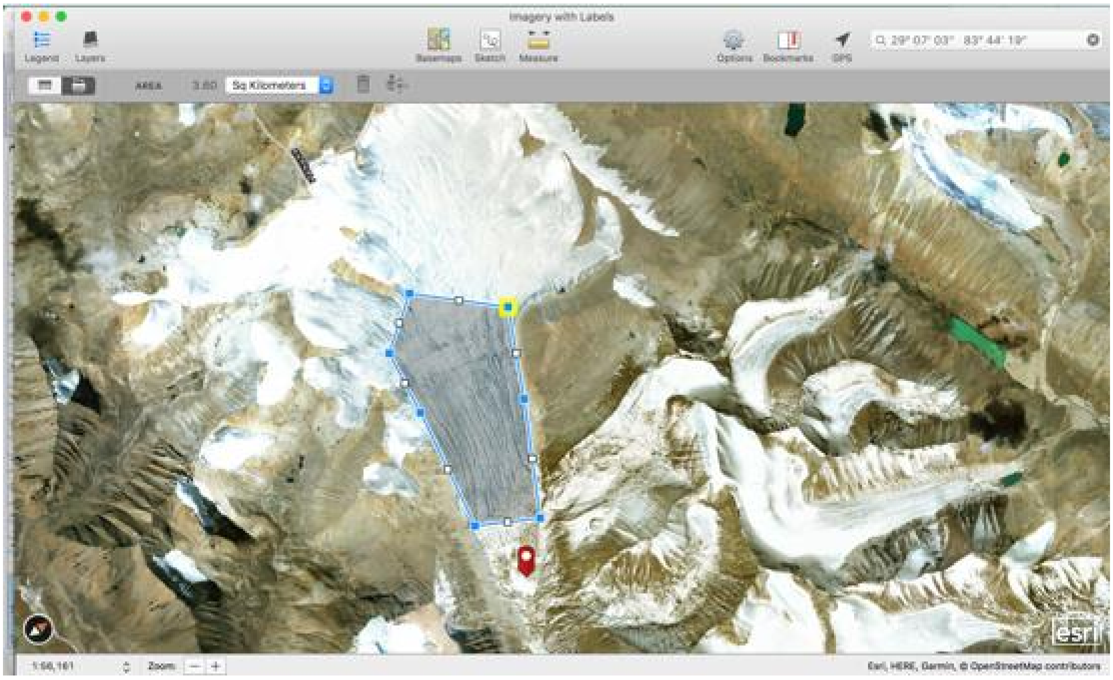


10. Kali Gandaki Unnamed (29° 13’ 14” 83° 42’ 09”)



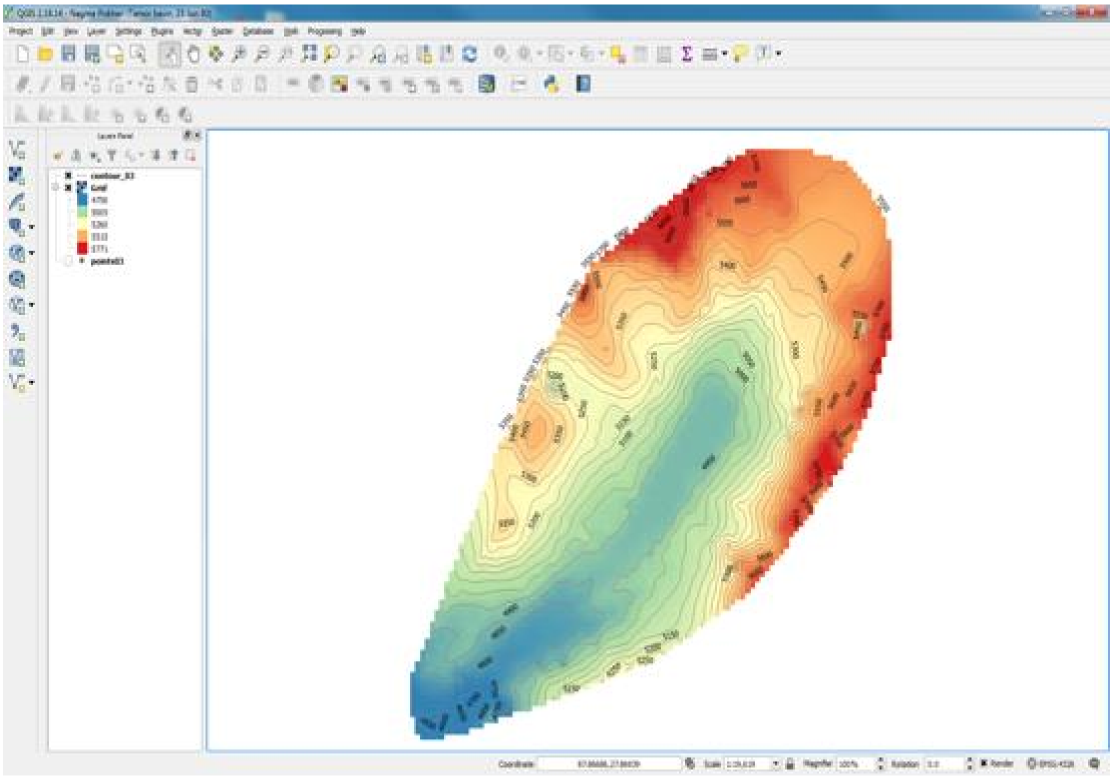


11. Kali Gandaki Unnamed (29° 07’03" 83° 44' 19")

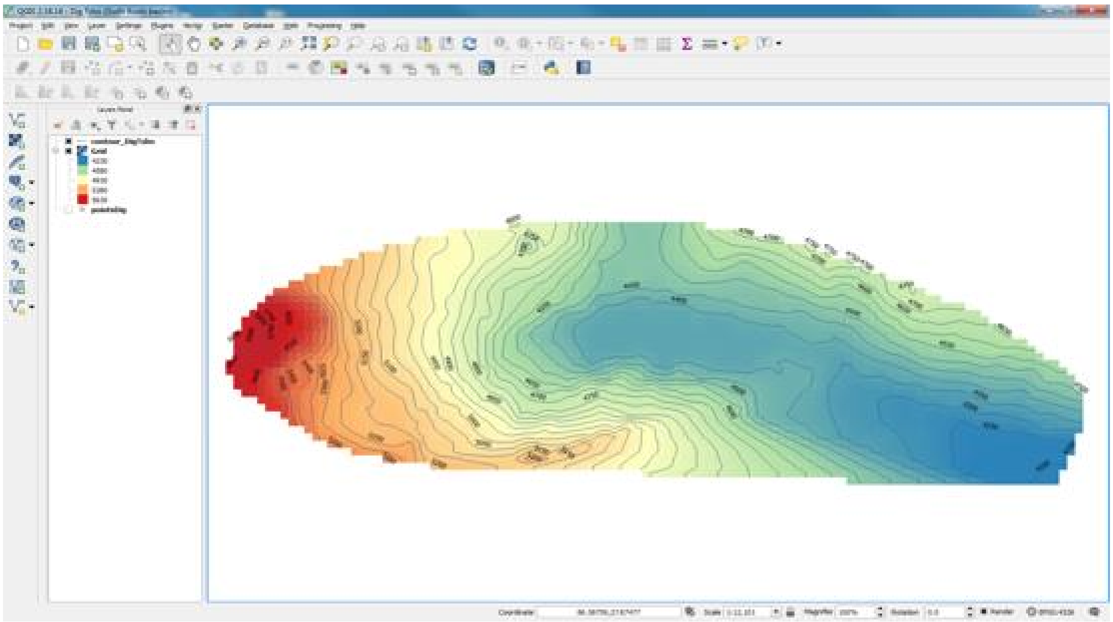


C. Existing PDGL Digital elevation modelling

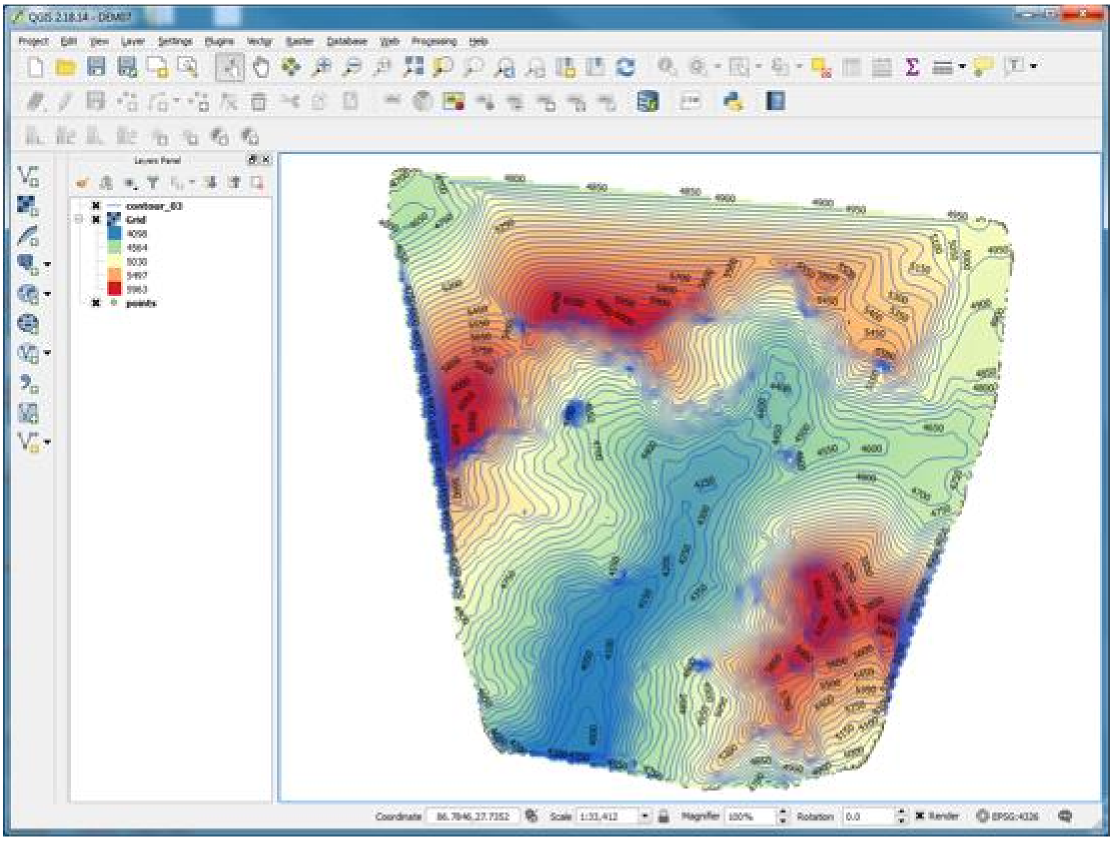
1. Nagma Pokhari, Tamor Basin



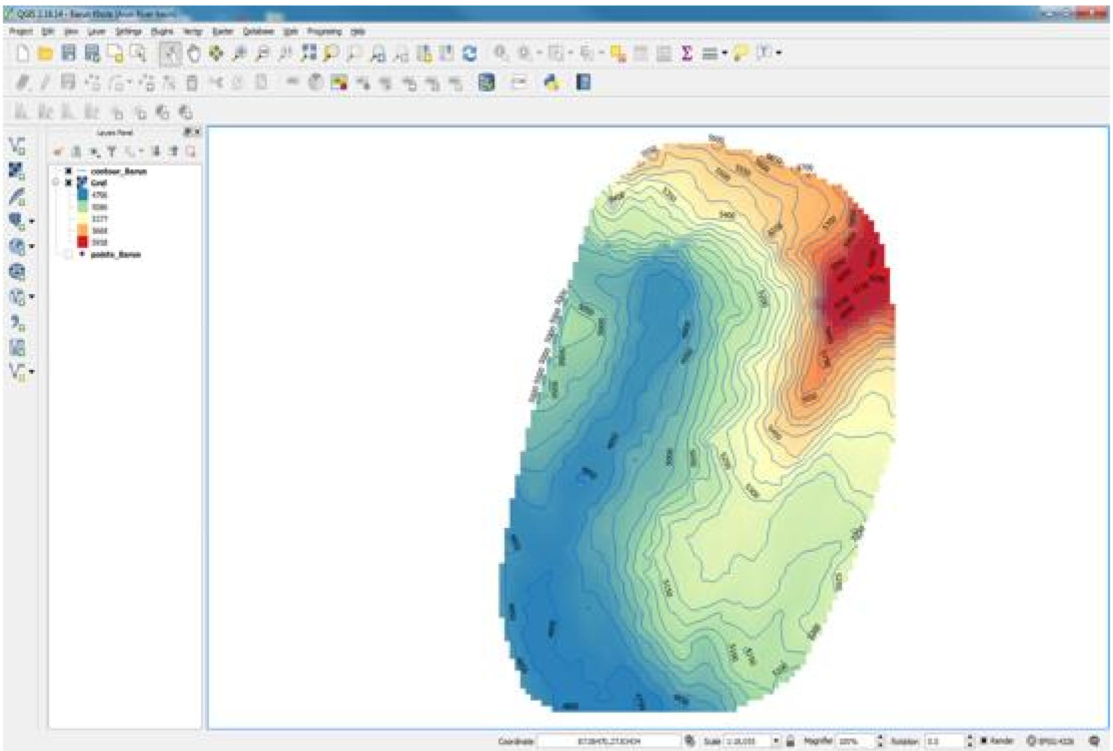
2. Dig Tsho, Dudh Koshi Basin



3. Tam Pokhari, Dudh Koshi Basin



4. Barun Khola, Arun River Basin



5. Kali Gandaki glacial lake