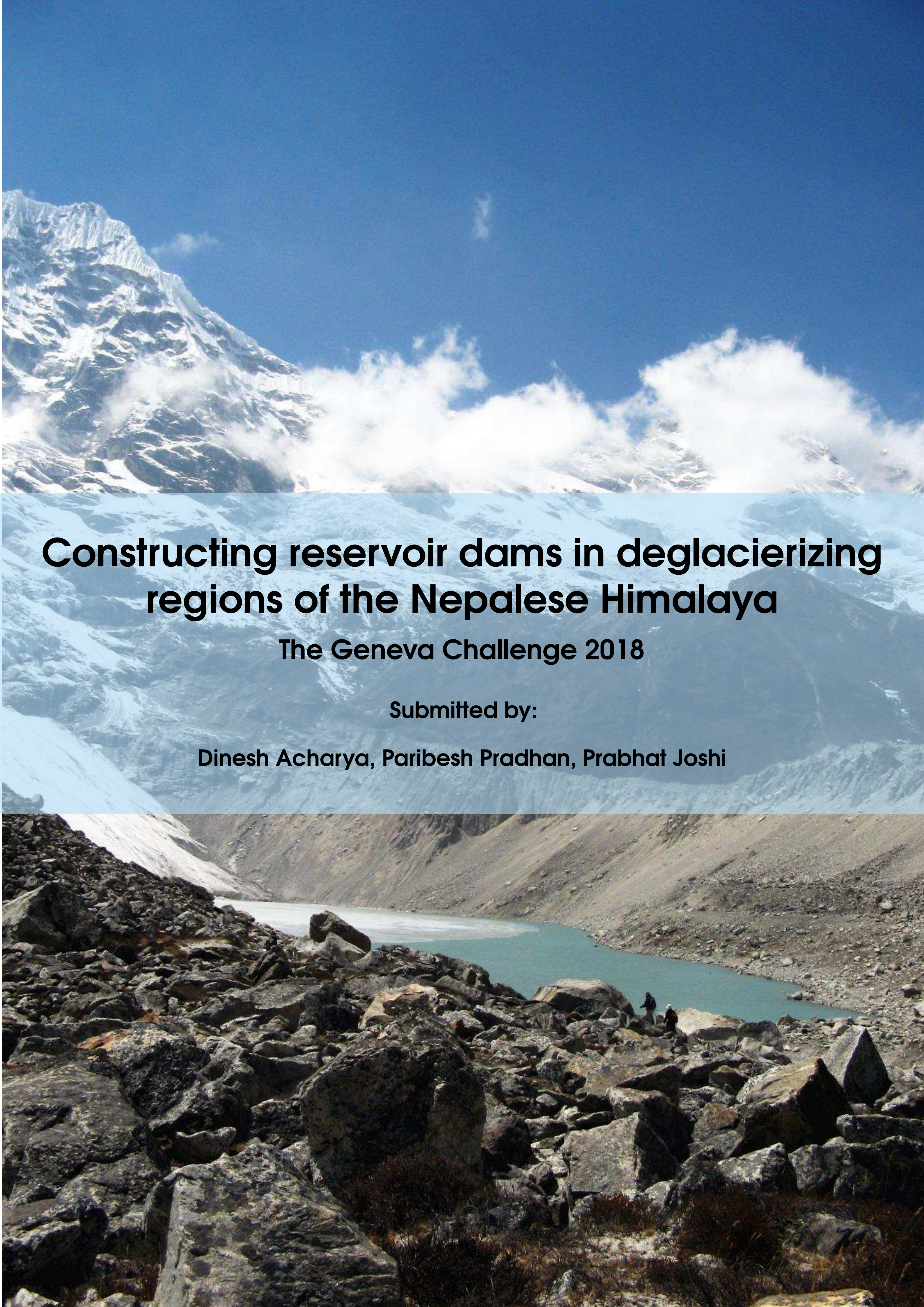

# Constructing reservoir dams in deglacierizing regions of the Nepalese Himalaya

## The Geneva Challenge 2018

Submitted by:

Dinesh Acharya, Paribesh Pradhan, Prabhat Joshi

**Authors' Note:**
This proposal is submitted to the Geneva Challenge 2018 by Master's students from ETH Zürich, Switzerland. All photographs in this proposal are taken by Paribesh Pradhan in the Mount Everest region (also known as the Khumbu region), Dudh Koshi basin of Nepal. The description of the photos used in this proposal are as follows:

**Photo Information:**

| | | |
|---|---|---|
| 1. | Cover page | Dig Tsho Glacial Lake (4364 m.asl), Nepal |
| 2. | Executive summary, *pp. 3* | Ama Dablam and Thamserku mountain range, Nepal |
| 3. | Introduction, *pp. 8* | Khumbu Glacier (4900 m.asl), Mt. Everest Region, Nepal |
| 4. | Problem statement, *pp. 11* | A local Sherpa Yak herder near Dig Tsho Glacial Lake, Nepal |
| 5. | Proposed methodology, *pp. 14* | Khumbu Glacier (4900 m.asl), Mt. Everest valley, Nepal |
| 6. | The pilot project proposal, *pp. 20* | Dig Tsho Glacial Lake (4364 m.asl), Nepal |
| 7. | Expected output and outcomes, *pp. 26* | Imja Tsho Glacial Lake (5010 m.asl), Nepal |
| 8. | Conclusions, *pp. 31* | Thukla Pass or Dughla Pass (4572 m.asl), Nepal |
| 9. | Bibliography, *pp. 33* | Imja valley (4900 m.asl), Nepal |

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# Executive Summary

Climate change is one of the greatest challenges of our time. The heating of the oceans, sea level rise, ocean acidification and coral bleaching, shrinking of ice sheets, declining Arctic sea ice, glacier retreat in high mountains, changing snow cover and recurrent extreme events are all indicators of climate change caused by anthropogenic greenhouse gas effect.

The melting of glaciers and ice are the most palpable evidence of climate change in high mountains all around the world as they act as barometers of global warming. In the last few decades, many pro-glacial lakes have emerged and expanded as a result of glacier retreat - a deglaciation process in high mountains. This is a cause for concern because glaciers have a special function in the environmental system. They play an important role in the hydrological cycle by acting as natural water reservoirs to regulate the flow of water into streams and rivers downstream during dry periods when there is no water available from snow melt and rain. Studies suggest that most of the high mountain glaciers will either disappear or drastically diminish in size and ice mass by the end of the $21^{st}$ century, leaving a fragile deglaciated environment of bare bedrock, loose debris and steep slopes, sparse vegetation and a lot of lakes. Therefore, it is imperative to think how such environments can be managed and if there are ways to mimic the hydrological function of glaciers in the environmental system.

We propose an unconventionally bold and provocative project where the hydrological function of glaciers in deglaciated high mountain environment is resuscitated by constructing reservoir dams, particularly where glacial lakes exist or areas where new glacial lakes can form in future. To meet the aim of this project, a series of actions is proposed, starting from detecting the changes in glacier mass. Machine learning algorithm is proposed to exploit the available time-series satellite data to predict depletion of glaciers as well as detect their depletion rate. This will be complemented using remote sensing techniques to obtain information about glacier geometry, elevation, terminus positions, accumulation, and ablation rates, and the overall mass balance of the glacier. This will also provide information about the amount of water that can be accumulated in glacier lakes, and consequently the potential deficit that can be mitigated by constructing a reservoir. The risks of outburst floods will be shown in a hazard map using simulations from hydrological-hydraulic modeling tools and geographic information system.

The core of this proposal is to develop a methodology to obtain information about the geomorphology and glacier geometry from machine learning algorithms and remote sensing techniques, which can then be applied to verify and select the most appropriate site through field investigations and surveys. After this selection, a Participatory and Integrated Planning (PIP) procedure and multi-criteria decision analysis (MCDA) can be implemented to finalise and define the operational and management process for the reservoir dam at a later stage. PIP and MCDA are proposed to ensure that key stakeholders' viewpoints is considered, including local stakeholders, in the decision making process of the reservoir operation.

On the whole, the project entails a climate smart approach that includes both mitigation measure and adaptive response - to build resilience among various stakeholders and local communities downstream. Further, it also aims at addressing the cross-cutting issues of poverty alleviation and the Sustainable Development Goals (SDGs). The underlying goal is to manage the risks and uncertainties associated with climate change and turn its challenges into new opportunities. For the purpose of this contest, a pilot project of Koshi basin in the Nepalese Himalaya is considered as a case-study, and the linkages and benefits of such approach to energy security, environmental sustainability, food security, agriculture, biodiversity, migration, displacement and disaster risks are discussed.

# Team information

## Dinesh Acharya

Dinesh Acharya completed his undergraduate studies from Jacobs University Bremen, Germany in mathematics. Currently, he is pursuing an M.Sc. in Computational Science and Engineering at the Swiss Federal Institute of Technology (ETH Zürich) with specialization in Robotics. He is interested in the application of Computer Vision and Machine Learning. He has experience in learning from spatio-temporal data. In particular, his interests include unsupervised representation learning from videos. Lately, he has been working on generative models for videos.

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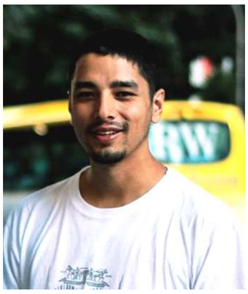
## Paribesh Pradhan



Paribesh has an interdisciplinary background with a Bachelor's degree in Electronics and Communication Engineering (Nepal) and an MSc. in Physical Geography with minor in glaciology from University of Zürich (Switzerland). At present, he is pursuing a Master of Advanced Studies in Sustainable Water Resources at ETH Zurich. Paribesh has work-experience in climate change adaptation and sustainable mountain development with the United Nations Environment Programme – Regional Resource Center for Asia Pacific (Thailand), International Center for Integrated Mountain Development (Nepal), and the Mountain Forum Secretariat (Peru). In 2012, he trekked east to west of the Nepal Himalayas to document the impact of climate change on mountain communities. Most recently, he was part of the Antarctic Circumnavigation Expedition – Leg 0 organized by the Swiss Polar Institute.

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## Prabhat Joshi

Prabhat completed his Bachelor's degree in Environmental Engineering from Kathmandu University (Nepal) in 2015. After two years of work experience, he started his Master's Degree in Environmental Engineering at ETH Zürich in 2017. He is specializing in Urban Water Management and is focusing his research on urban hydrology and drainage systems. He wants to bring low impact development (LID) strategies into the mainstream of urban drainage planning. He is also interested in investigating the impacts of climate change on drainage systems, and understand how sudden and gradual increases in water flow affect the performance of the systems.

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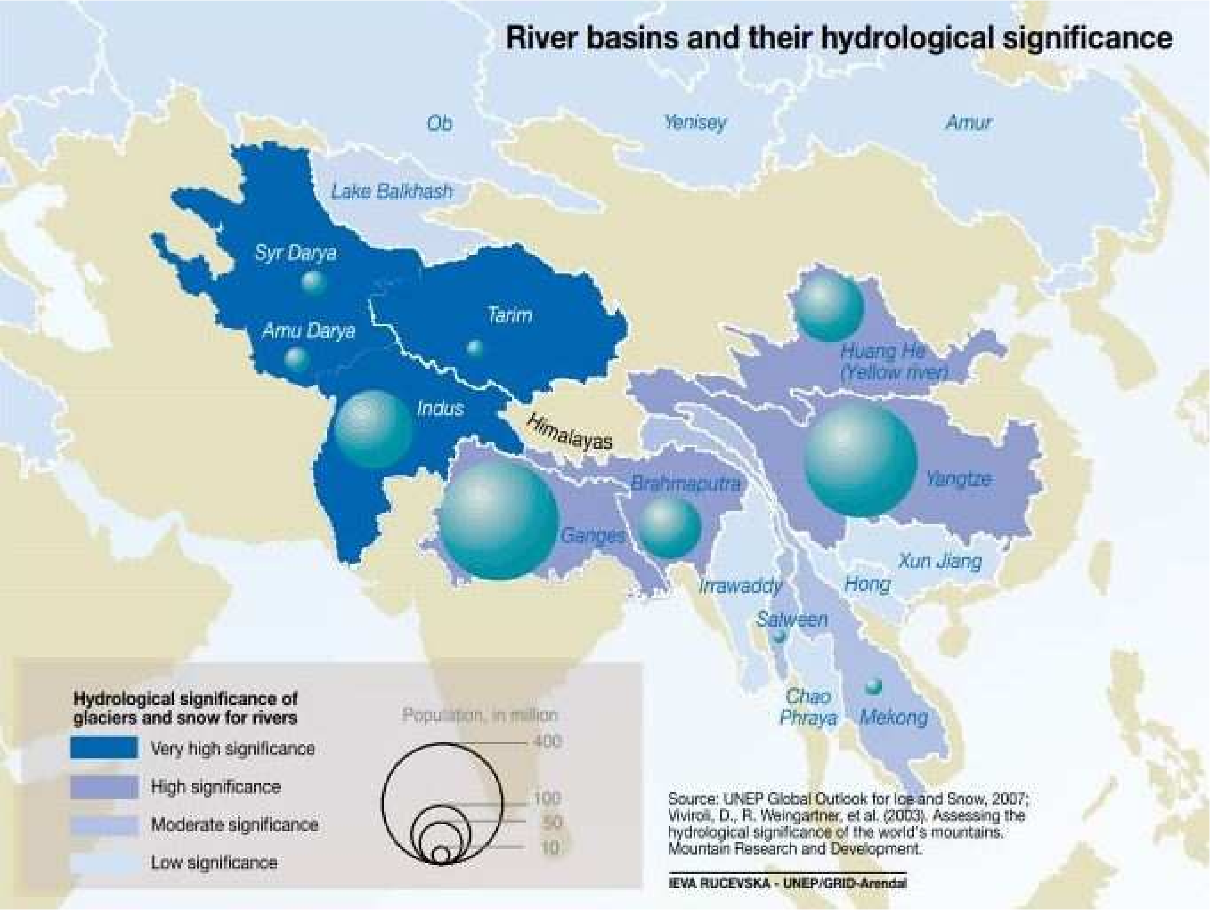
# Contents

# 1. Introduction

The increased concentrations of carbon dioxide, methane and nitrous oxide due to human activities have been the dominant cause of warming of the atmosphere and ocean - rising the sea level and diminishing the amounts of snow and ice on the land surface since the mid-$20^{th}$ century (IPCC, 2014). This is the consensus of more than 97 percent of actively publishing climate scientists and most of the leading scientific organizations from all over the World (Cook et al., 2016; NASA, 2018).

Approximately 10 percent of Earth's land surface is covered by ice (Tweed and Carrivick, 2015). Most of the global changes and shifts which are a vivid indication of changing climate are more pronounced in this frozen water part of the Earth system, also known as the cryosphere (NOAA, 2018). Every year between 1993 and 2016, the ice sheets in Greenland have lost an average of 281 billion tons of ice mass while Antarctica lost 119 billion tons on average, thus contributing to global sea level rise of 20.32 centimeters (NASA, 2018). Similarly, the Arctic sea ice has also lost both the extent and its thickness as it continues to warm more rapidly than the global mean temperature (IPCC, 2014). The warming of the Arctic region in the high northern latitudes will also impact near-surface permafrost (IPCC, 2014). The degradation of permafrost in the Arctic tundra in the high northern latitudes, the declining ice mass in continental ice sheets and polar ice caps and the diminishing snow cover and early snow melt along with the retreating glaciers in the high mountains and other extreme environments, all of which are a part of the cryosphere, provide direct and visual evidence of changes in temperature and the climate (NSIDC, 2018).

In the "water towers of Asia" - the Hindu-Kush Himalayan (HKH) region shown in Figure 1.1, these occurrence of ice mass changes and glacier retreat are already visible, signaling to the changing climate (Messerli and Ives, 1997; Bolch et al., 2012; Ashraf et al., 2017). The HKH region hosts 15,000 glaciers in an area of approximately 33,344 $km^2$ and 8,790 glacial lakes (Ives et al., 2010). Although glacial lakes can naturally exist in a mountain environment, their number and size are growing rapidly because of the glacier retreat caused by enhanced melting due to rising temperatures (Haeberli et al., 2016; Ashraf et al., 2017). These lakes are unstable and dammed by natural deposits of ice, bedrock, moraine or landslide debris as shown in Figure 1.2 (Tweed and Carrivick, 2015). In the past 40 years, both the number and area of glacial lakes have increased throughout the HKH region (Shrestha et al., 2017; Ashraf et al., 2017; Zhang et al., 2015). Today, there are more than 200 potentially dangerous glacial lakes in the HKH region which could breach their moraine dams and create glacial lake outburst floods (GLOFs) in the downstream valleys (Ives et al., 2010). It is expected that the occurrences of GLOFs will only increase in the future due to climate change as permafrosts thaws and glaciers shrink at an alarming pace exposing mountain slopes and destabilizing the environment. This will increase the potential of landslides, avalanches and debris flow hazards which can hit the glacial lake and trigger an outburst flood (Nussbaumer et al., 2014).



Source: UNEP Global Outlook for Ice and Snow, 2007; Viviroli, D., R. Weingartner, et al. (2003). Assessing the hydrological significance of the world's mountains. Mountain Research and Development.

IEVA RUCEVSKA - UNEP/GRID-Arendal

Figure 1.1: **River basins in the HKH region and their hydrological significance (GRID Arendal, 2010)**

Nepal, which lies in the HKH region is reported to have 2168 glacial lakes covering an area of approximately 128 km$^2$ (Shrestha et al., 2017). Out of these, 21 lakes have been identified to be highly susceptible to outburst floods (ICIMOD, 2011). Hydro-geologic and cryospheric investigations of these glacial lakes have identified several factors as precursors to outburst floods such as the local micro-climate, topography, glacier dynamics, and moraine dam stability (Benn et al., 2012). The latter is prone to melting, gravitational collapse or failure due to natural hazards like earthquakes and avalanches. This is of major concern in Nepal as it is on a seismically active region. In addition, several studies have shown that many of the glacial lakes present in Nepal today were formed only after the mid-1950s and they grew drastically since the 1970s as a result of thinning and retreating of glaciers (Chalise et al., 2006; Shrestha et al., 2017; Haritashya et al., 2018). As the area of glacial lake expands further increasing the pressure on the moraine dam, it poses a high risk for an outburst flood (ICIMOD, 2011; Shrestha et al., 2017). It is thus highly likely that these landscapes will evolve in future having only bare bedrock, loose debris, sparse vegetation, lot of lakes and steep slopes with thawing permafrost as shown in Figure 1.3 (Haeberli et al., 2017). However, it is not just the glacial environment that is going to change in the future but it will impact more than half a billion people downstream in the Ganges basin as shown in Figure 1.1.

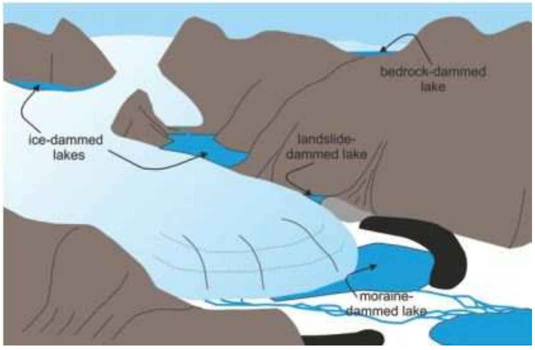


Figure 1.2: **Different damming mechanisms for glacial lakes (Tweed and Carrivick, 2015)**

The Ganges basin drains all the rivers from Nepal and a declining trend in snow cover area has already been observed for winter and autumn seasons in this basin (Gurung et al., 2011). According to a more recent study, in high mountains of Nepal, the highest positive trend for maximum temperature has been observed in winter season while in the middle mountains and flat plains of Nepal, the highest positive trend have been observed in the monsoon season (Salzmann et al., 2017). There is also a significant trend for extreme temperature in all parts of Nepal and for extreme precipitation in northwestern and northern parts of Nepal (Salzmann et al., 2017). This suggests similar conclusions made by another recent study which concludes that high mountain catchments in Nepal will have an increase future runoff with limited seasonal shift in hydrological regime and an increase in peak flows and flood extremes (Ragettli et al., 2016). The increased runoff is a result of enhanced ice melt in basins with high elevation and glacierization but it is expected to decrease after few decades as the size of the glacier diminishes (Viviroli et al., 2011). The changes in winter precipitation falling as snow and the total runoff will eventually impact the future water availability scenario at upstream, middle stream and downstream of the catchment. It will pose unsurmountable challenges in the integrated water resource planning and management for the future generation.

Thus in this proposal, the future issues and challenges of high mountain glacier environments due to impact of climate change are discussed, and an integrated adaptation and mitigation structural measure to address this multi-faceted problem is proposed. To establish a rationale behind the approach and to describe the proposed methodology, this proposal has been categorized into several sections. Section 2 describes hydrological function of glaciers, the problem of shrinking glaciers and growing glacier lakes due to climate change and how to turn challenges into opportunities. This is followed by the proposed methodology in Section 3. In Section 4, outcomes with pros and cons of this approach are discussed. Section 5 consists of concluding remarks.

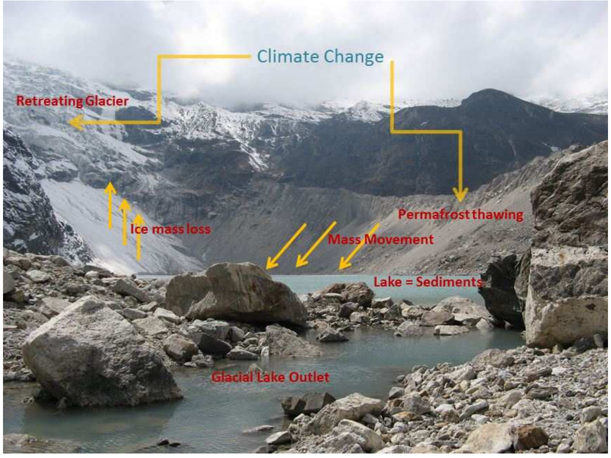


Figure 1.3: **Illustration of climate-glacier interaction, Dig Tsho glacier lake in Nepal [Adapted: (Tweed and Carrivick, 2015), *Photo: P Pradhan*]**

# 2. Problem statement

## 2.1 Rationale

When temperatures are low and there is more snowfall (accumulation), glaciers gain mass and if the net accumulation is positive year after year for a long period of time, they advance, increasing in size and volume. However, they lose this mass and retreat if temperatures are high, which enhances the melt rate (Bolch et al., 2012). The health of any glacier i.e. whether they are advancing or retreating, is measured through this mass balance budget.

Glaciers also have a special function in the environmental system. They play an important role in the hydrological cycle by acting as a natural water reservoir. They store water in the form of blue ice and supply water to the streams and rivers downstream during dry seasons when there is no water available from snow melt or rain. With the rising temperature and changing climate, it is highly likely that most of the glaciers will drastically diminish in size and deplete in ice mass such that it will vanish completely leaving a deglaciated environment of barren and fragile landscape. Such new landscape evolution could disturb the critical state of the mountain geomorphology and may alter the operations of biophysical fluxes such as water, sediment and nutrients by disconnecting the elements of fluvial systems such as hillslopes, channels and floodplains. The deglaciation process of the melting of glaciers and ice are therefore the most palpable evidence of changing climate as they act as barometers of climate change (Tweed and Carrivick, 2015). Many pro-glacial lakes emerge at the edge or margin of the glaciers as they retreat because of rapid melting due to rising temperature.

With the current warming estimates, the glaciers in Tibetan Plateau is likely to recede from an area covering 500,000 km$^2$ to 100,000 km$^2$ by the year 2035 (Xu et al., 2009). This means that as the glaciers recede at a rapid pace, discharge in rivers will first increase thus increasing the water availability. However, over a long period of time when the glaciers disappear, the flow in these rivers will also decrease creating water stress especially during dry periods (summer and early autumn) (Bolch et al., 2012). Besides, the demand for water supply will only increase in future mainly due to drivers such as population growth and urbanization. This relationship between climate change, glacier and water demand is illustrated in 2.1.

It is crucial to think how the hydrological function of glaciers in high mountain environment can be resuscitated to provide continuous flow of water not just for the communities living downstream but also

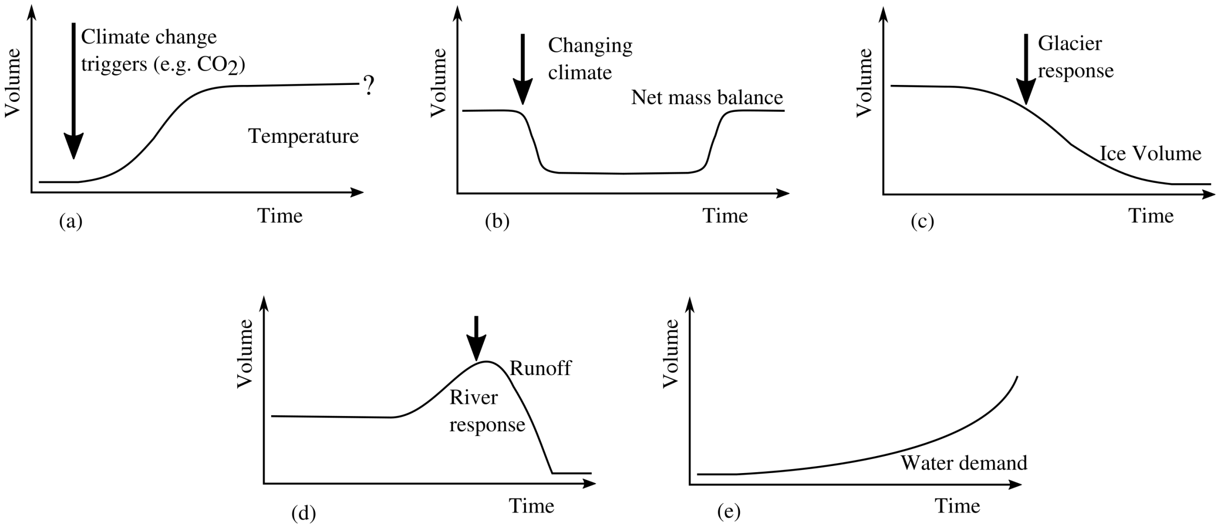


Figure 2.1: **a) Effect of climate change, b) Negative (temporarily) mass balance, c) Change in ice volume, d) Discharge regime, e) Water supply demand (Xu et al., 2009)**

for the ecological sustenance of the riverine freshwater aquatic habitat and other terrestrial ecosystems. Are there ways to mimic this hydrological function of glaciers in such fragile deglaciated high mountain environmental systems? Is it possible to manage such extreme environment and its associated vulnerability, and turn such risks into rewards? Using reservoir to manage water as well as flood and drought control is not a new concept but at high altitude, it is a provocative proposition, one that requires courage and state-of-the-art engineering design.

## 2.2 Aim

To manage risks and uncertainties associated with climate change in high mountain glacier environments and turn these challenges into new opportunities while ensuring a secure environment for sustainable livelihood and water–energy–food security nexus.

## 2.3 Proposal

Construct a reservoir dam or a network of reservoir dams that would mimic the hydrological function of receding glaciers and mitigate the GLOF threat from an advancing glacier lakes while also using it to redistribute water in space and time applying the principles of participatory and integrated approach to water resources planning and management scheme.

## 2.4 Plan of action

The plan of action are categorized under several stages to give an overall view of this proposal.

### Stage 1: Reconnaissance and conceptualization

- Select a high mountain geographical region to apply this approach.
- Predict future landscape evolution and detect deglaciation sites with potential glacial lake formation or existing lakes that are growing.
- Perform spatial variability assessment to check the elevation of the ice mass on these sites as they may also influences the melt regimes (Bolch et al., 2012) and select the sites where the variation is high.
- Create a criterion based on elevation gradient and rock or soil profiles, and map the most suitable sites based on the above analyses.

- Collect the available hydrological and meteorological observation data from the surrounding field stations in those areas to simulate hydrological models to analyze if there will be sufficient runoff contribution from the rain, snow and ice to fill and sustain the reservoir dam based on various climate scenarios.
- Collect the government census data to get a sense of the population density and socio-economic status of the downstream communities such as: health, education, livelihood, occupation etc.

**Stage 2: Field surveys**

- Conduct field exploration and engineering surveys. This includes: geophysical and contour survey as well as environmental impact assessment.
- Risk assessments: system risk and stability analysis under various climate change scenarios.
- Choose the most appropriate location to build a reservoir dam.

**Stage 3: Action plan and budget estimation**

- Develop a plan of action to construct a suitable dam that would mimic the hydrological function of receding glaciers on proglacial lake environment in consultation with glaciologists, geophysicists, environmental, civil and structural engineers, as well as economists and anthropologists to analyze the impact on livelihoods.
- Estimate the budget and prepare a financial report and proposal.

**Stage 4: Financing**

- Get financial approval and secure funding.

**Stage 5: Implementation**

- Implement the plan of action and build a reservoir dam.
- Assess after each quarter of the year.

**Stage 6: Water resource management**

- Once the dam is built, a participatory and integrated planning (PIP) procedure based on stakeholders involvement, social learning, structured process, integration and rationalization and transparency principles could be applied (Soncini-Sessa et al., 2007b,a). It will help to design reservoir operating policies that can then used to regulate the flows in order to assist activities such as hydropower production, irrigation and agricultural productivity, industrial and civil uses and flood risk mitigation based on their priorities.

## 2.5 Scope of proposal

The Himalayas occupy an area of approximately 0.65 million km$^2$ of which around 22,800 km$^2$ is covered by glaciers (Bolch et al., 2012; Nie et al., 2018). Given such huge spatial coverage of the Himalayas, the complexity dimension of this concept and magnitude of the project in relation to the scope of this contest, it is not feasible to demonstrate all the stages mentioned above. Furthermore, there are no adequate field based information available as no technical surveys have been conducted. The core idea behind this proposal is to outline an alternative paradigm displaying analytical rigour based on academic research and critical thinking, and pathways to its practical implementation. Building dams has a huge cost implication, involving many local, national and international actors, multinational companies and agencies. This proposal also does not account and delve into methodology and processes for construction of the structural design of the reservoir dam but rather serve as a precursor to this stage. Therefore, the objective here is to develop a methodology and tool by taking plan of action defined in stage 1 using remote sensing techniques and machine learning algorithms.

# 3. Proposed methodology

The overview of the proposed methodology is shown in Figure 3.1 and described in detail in sections 3.1 – 3.3. Deep spatio-temporal learning will be used for initial identification of high mountain regions with glaciers. Based on past data, their current state will be identified. Finally, using future prediction techniques, possible evolution of glaciers will be inferred from past data. This will be further validated through visual assessment and remote sensing analysis. This is the first step of the project which will generate a map where reservoir dams could likely be built and where there is significant hazard potential. This is important because it will be the basis for identifying the site and proceeding from stage 2 - 6 mentioned in Section 2.4. The steps of this methodology are explained in detail in the following sections.

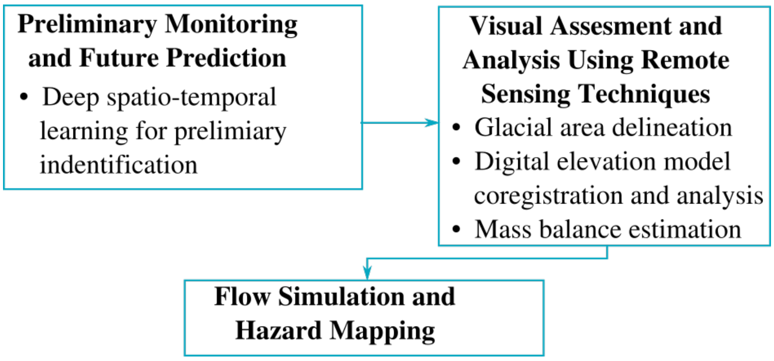


Figure 3.1: **Overview of the proposed methodology to construct reservoir dams in deglacierized regions**

## 3.1 Identification of regions with glaciers and assessing their current and future state

The regions prone to glacial lake formation are spread over large geographic areas that are often remote and inaccessible. Surveying such large regions of glaciers from land or by air requires huge amount of resources. Furthermore, static images do not provide any information as to whether a glacier is increasing in volume, receding or in constant state. Static image is also insufficient to predict how the glacier will evolve in future. To this end, this proposal leverages current advances in deep spatio-temporal learning algorithms and openly available time series satellite data for two purposes: monitoring current state of glaciers and predicting future evolution of glaciers. Deep learning algorithms provide a framework for statistical inference on large scale data and have been widely employed for purposes ranging from language translation to age prediction from facial images. Deep spatio-temporal learning algorithms perform statistical inference on spatio-temporal data such as videos, time-series satellite images or temporal medical images. Recently they have also been employed for classification of land cover and crop types using Landsat images (Kussul et al., 2017). Such techniques will serve in preliminary monitoring and identification of regions prone to glacial lake formation. After identification of such regions further high fidelity models can be used to accurately model glacial lake formation.

To monitor the current state of glacier, given time-series image can be categorized into one of the four categories: presence of receding glacier, presence of glacier in constant state, presence of glacier with increasing volume or absence of any glacier. Labeling a give region into one of the above categories provides preliminary insight about the current state of the glaciers. For classification, we propose to use either a C3D model (three dimensional convolutional neural network) (Tran et al., 2015) or a two-stream model based on optical flow and appearance (Simonyan and Zisserman, 2014). Such models have been previously used for human action classification in videos with great success. However, these models are equally relevant in time-series satellite image analysis as the data structure of a time-series satellite image is same as that of the videos. The use of a C3D model for classification is illustrated in Figure 3.2. One of the challenges of this approach is the collection of training data. This can be solved by either manually labeling the data using Amazon Mechanical Turk, using widely available historical data or using simulated data generated by using Rapid Mass Movements (RAMMs) model available in ArcGIS or ENVI softwares.

Similarly, in order to predict the future evolution of glaciers from historical time-series satellite images, we propose to leverage future prediction techniques that have already been applied to the videos. Future prediction falls under conditional video generation where generation of future video frames is conditioned on past frames of the video. This has previously been explored by computer vision community for application in autonomous driving and robot arm manipulation ( Finn et al. (2016)). The basic idea behind future prediction is illustrated in Figure 3.3. The encoder encodes or summarizes the information present in the past frames of a video clip into a vector representation. This hidden representation is then used by generator to interpolate the past frames to generate future frames. The interpolation uses statistical information such as how other glaciers in similar state behaved in the past or how glaciers in other geographic locations but in similar state behaved to predict how given glacier will evolve in future given its current state. As mentioned above, a time-series satellite image can be treated as a video clip and can be applied to predict future evolution of glaciers. Furthermore, to account for local weather patterns or geographic information, future prediction can be also be conditioned on the available additional information. The training data for future prediction is comparatively easy to generate as historical time-series images can be split into hypothetical past frames and hypothetical future frames.

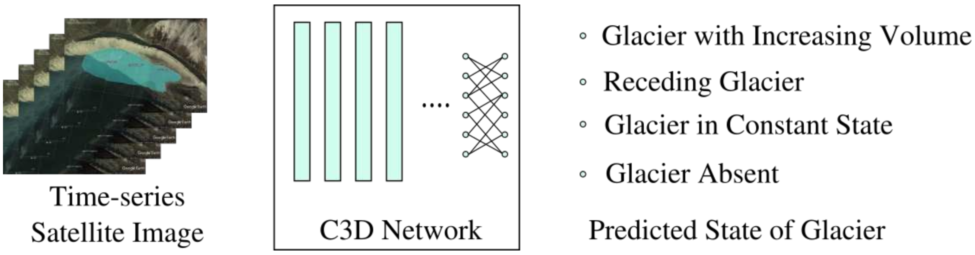


Figure 3.2: **Concept for identification of current state of glacier in a time-series satellite image**

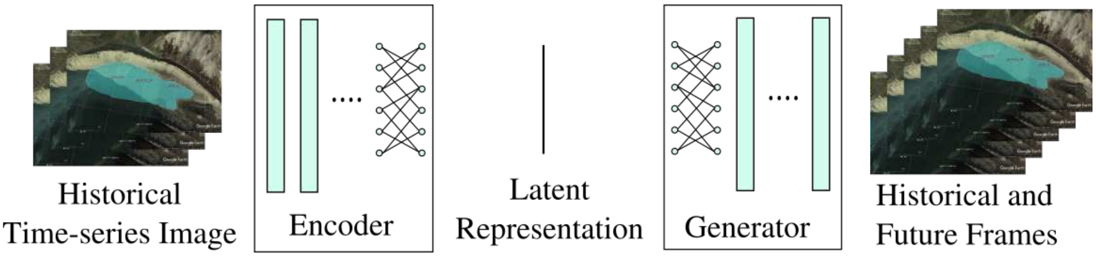


Figure 3.3: **Concept for predicting future state of glacier**

## 3.2 Visual assessment and analysis using remote sensing techniques

After using deep learning for identification of regions with receding glaciers, a detailed visual assessment using satellite-based platforms (optical images) such as Google Earth Engine will be used to get an idea of the topography as well as glacier geometry. This will be used to identify locations within the region of interest that require urgent intervention. For example, glaciated regions in the upstream of a settlement or a hydropower plant will be prioritized above those that are located in remote areas with no or relatively less conspicuous impacts.

The application of remote sensing techniques to obtain data for glaciological applications has been widely practiced following the increasing availability of images of adequate temporal and spatial resolutions. This has also allowed sensing information of glaciers in remote and often inaccessible locations, many of which are located in the Himalayas (Racoviteanu et al., 2008; Raup et al., 2000). With regards to this proposal, optical remote sensing techniques are proposed to obtain information about glacier area, length, surface elevation, terminus positions, accumulation and ablation rates, albedo, and the overall mass balance gradient (Haritashya et al., 2018; Racoviteanu et al., 2008). This will, in turn, help obtain information regarding the glacier hypsometry and topography which are vital to locate appropriate area for reservoir construction.

Available literature on the application of visible and thermal infrared remote sensing data largely converge in favor of ASTER data to determine glacier thickness and volume estimations, assess pixel-level volumetric changes using digital elevation models (DEMs), enabling determination of annual mass balances of glaciers (Racoviteanu et al., 2008; Bishop et al., 2000; Kargel et al., 2005). This is owing to the low spatial resolution of ASTER ($\sim$15m in VNIR bands), high spectral resolution (with with 3 VNIR bands and 6 mid-IR bands), adjustable sensor gains, flexible image acquisition time ($\sim$16 days or less), and data availability at free of cost in selected platforms (Racoviteanu et al., 2008). As such, ASTER data will be used for the application under proposal to obtain information as described in sub-sections 3.2.1 – 3.2.3.

### 3.2.1 Glacier area delineation

The changes in climatic conditions and the consequent impacts on glaciated regions are indicated by the changes in the glacier area and terminus positions, both of which will be extracted from satellite images. These images will then be combined with the DEMs to derive glacier parameters such as hypsometry and minimum/medium elevations, which has been described in Section 3.2.2. In doing so, high reflectivity (albedo) of snow and ice covers will be used to determine normalized difference snow index (NDSI) as shown in Equation 3.1. This will allow the segregation of glaciers from rocks, soils, and vegetation using a threshold value to obtain a binary map of glaciated and non-glaciated area. For example, an NDSI value of 0.6 has been used to identify glaciers in Peru (Hall et al., 1995); a similar value will be identified for the region of interest after image analysis. Furthermore, in order to separate glaciers from debris (prevalent in glaciers and moraine dams), a false color composite of thermal bands will be used taking advantage of the temperate differences between the two types of surfaces. The use of thermal bands will also be used to estimate the thickness of debris and will be inferred to gain an estimation of the melt rate. The obtained information will be verified using manual inspection during field survey in stage 2.

$$NDSI = \frac{R_{0.66} - R_{1.6}}{R_{0.66} + R_{1.6}} \tag{3.1}$$

where, $R_{0.66}$ and $R_{1.6}$ are reflectance values at wavelengths $\lambda$ = 0.66 $\mu m$ and 1.6 $\mu m$ respectively.

### 3.2.2 Digital elevation model (DEM) co-registration and analysis

The DEM will be generated by co-registering several DEMs of the region, that will enhance the horizontal and vertical accuracy while also providing information regarding the elevation change rate (Haritashya et al., 2018). An elevation dataset will be initially developed using images from the Shuttle Radar Topography Mission (SRTM) which will be 'treated' to fill the inherent voids. This will provide a hydrologically sound reference elevation data, although with slope-induced errors that are characteristic of SRTM dataset (Racoviteanu et al., 2008). To overcome this issue and minimize the artifacts, DEMs generated using ASTER dataset will be co-registered using stereo-correlation procedures available in most image processing softwares. Furthermore, in some regions where access to field investigation is possible, ground control points (GCPs) will be established to generate 'absolute' DEMs fitted to an appropriate coordinate system (Racoviteanu et al., 2008). The DEMs thus generated will be combined with ASTER images to determine the information of glacier geometry (length, termini and median elevations), mass balance, as well as information about their hypsometry and flow patterns.

### 3.2.3 Mass balance estimation

In order to compute the values of ice volume for a mass balance estimation, two methods will be used: volume-area scaling technique and geodetic method. The former is a simplified approach of obtaining information about ice volume which assumes that volume and lengths are related by power laws as shown in Equation 3.2, the scales of which are determined empirically (Oerlemans et al., 2007). This method assumes a steady state condition among climate, ice flow, ice geometry, and as such, will be used only to get an initial estimate.

$$\frac{V}{V_{ref}} = \left(\frac{L}{L_{ref}}\right)^{\eta} \tag{3.2}$$

where, $V_{ref}$ and $L_{ref}$ are reference volume and length respectively, and $\eta$ is a scaling coefficient ($\eta$ = 1.4-1.5 for glaciers with no change in width, and 2.4-2.5 for ice caps (Oerlemans et al., 2007))

For a more precise estimation, the geodetic method will be used which will measure the average elevation change over time from the DEMs constructed for the glaciers. The average elevation change will be multiplied with glacier area to obtain glacier volume, which will in turn be multiplied by the average value of ice density.

Having obtained the volume of ice, the mass balance will determined using the accumulation area ratio (AAR) method. First, the annual equilibrium line altitude (ELA), where the annual accumulation of snow is exactly balanced by the annual ablation, will be determined from the available DEM using the difference in the reflectivity (albedo) of the glacier surface. Then, AAR will be determined by calculating the area above and below the ELA which gives the value at which the glacier is in equilibrium with the climate zone of the region. To do so, the area above the ELA and below the ELA will be calculated. The results will be used to compile field-based mass balance measurements and AAR in regression analysis as expressed in Equation 3.3. This will be repeated for all the glaciers in the climate zone to get a single regression line for the region.

$$Bn = a * AAR + b \tag{3.3}$$

where Bn is the specific mass balance in water equivalent, AAR is the accumulation area ratio, and a and b are the slope and intercept values of the regression line respectively.

The mass balance will allow the determination of the potentially mitigable volume change as shown in Figure 3.4. This volume for a future scenario is the sum of all positive volume differences with respect to mean runoff volume for a reference scenario. This, in turn, will give an estimate of the size of the reservoir.

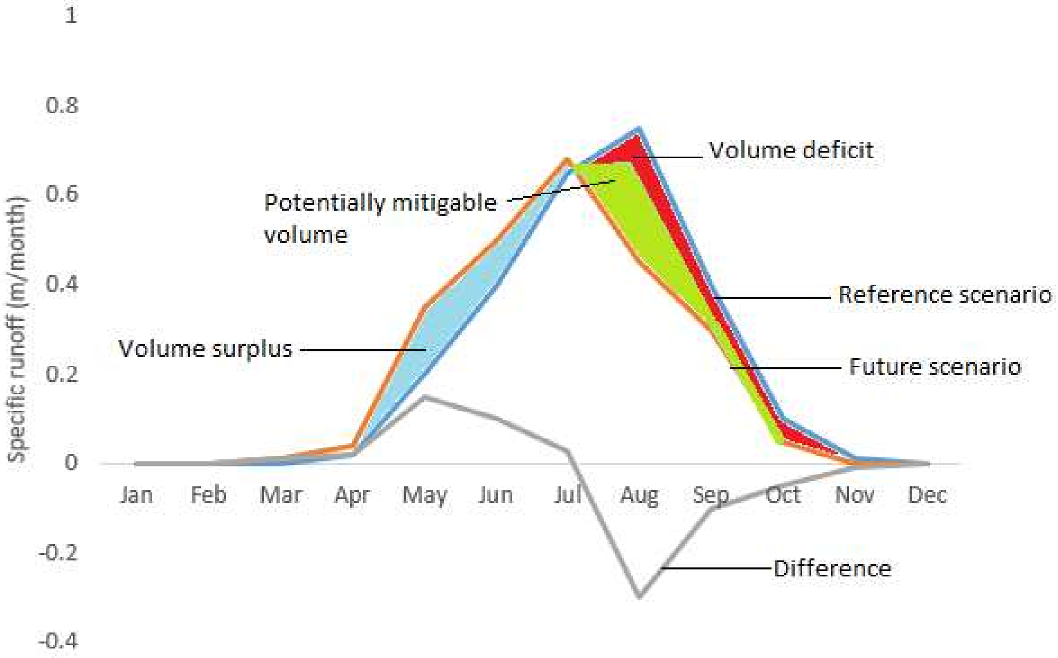


Figure 3.4: **Illustration of potential water mitigation due to reservoir construction [Adapted from Farinotti et al. (2016)]**

## 3.3 Flow simulation and hazard mapping

The schematic of the methodology proposed for moraine dam breach and flow simulation is shown in Figure 3.5. As shown in the figure, available DEM and geo-hydrologial data will be fed into HEC-RAS to simulate the flood in case of an glacier outbreak. The information will then be transferred to GIS to produce a hazard map (locations that are prone to inundation due to flood events). For this project, the use of HEC-RAS is proposed, which is a conceptual model that generates outflow hydrographs based on the breach geometry and breach development time (Westoby et al., 2014; HEC-RAS, 2014). The flow is modeled using 1-D St. Venant's equation for conservation of mass and momentum respectively as shown in Equations 3.4 - 3.5. On the other hand, the breach model will be regression based as developed by Froehlich (2008) for earthen and rock fill data sets, and as shown in Equations 3.6 and 3.7 for average breach width and breach formation time respectively.

$$\frac{\partial Q}{\partial x}+\frac{\partial A}{\partial t}=0 \tag{3.4}$$

$$\frac{1}{A}\frac{\partial Q}{\partial x}+\frac{1}{A}\frac{\partial\left(\frac{Q^2}{A}\right)}{\partial x}+g\frac{\partial h}{\partial x}-g(S_0-S_f)=0 \tag{3.5}$$

where $Q$ is the discharge, $A$ is the cross-section area, $t$ is time, $g$ is gravitational acceleration, $h$ is the cross-sectional averaged water depth, $S_0$ is the longitudinal bed slope, and $S_f$ is the friction slope.

$$B_{ave} = 0.27 K_o V_w^{0.32} h_b^{0.04} \tag{3.6}$$

$$t_f = 63.2(V_w/(g h_b^2))^{0.5} \tag{3.7}$$

where $B_{ave}$ is the average breach width [m], $K_0$ is constant (1.3 for over topping failures), $V_w$ is reservoir volume at time of failures [$m^3$], $h_b$ is height of the final breach [m], g is gravitational acceleration, and $t_f$ is the breach formation time [s].

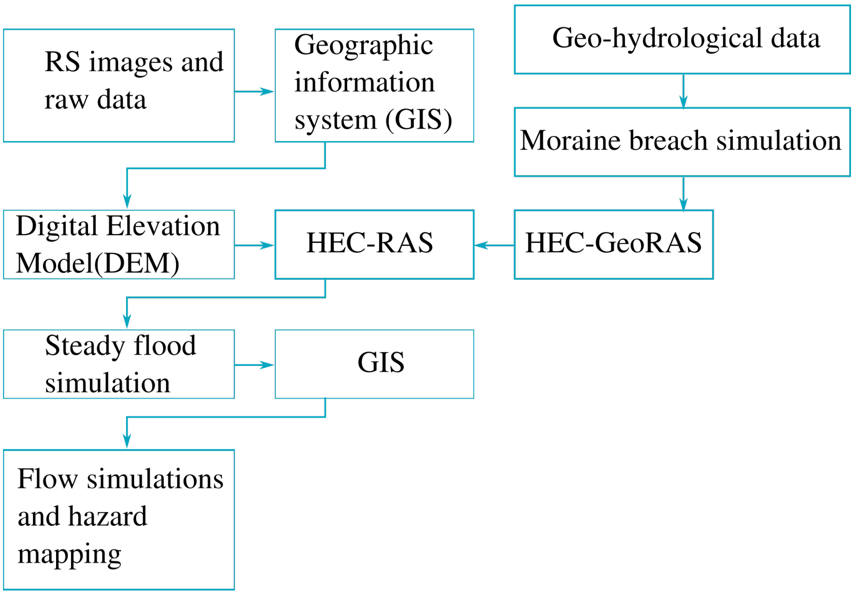


Figure 3.5: **Schematic of the methodology for flow simulation and hazard mapping**

# 4. The Pilot Project Proposal

## 4.1 A case study of Dudh Koshi basin in Nepal

The Dudh Koshi catchment in Nepal is selected to showcase how a pilot project can be implemented based using remote sensing techniques mentioned in Chapter 3. The Dudh Koshi catchment is the largest glacierized catchment in Nepal consisting of 278 glaciers, of which 70 percent of the area is covered by just 40 glaciers (Bajracharya and Mool, 2009). Almost all of these glaciers are retreating at rates between 10 to 74 meters per year as shown in 4.1 (Bajracharya and Mool, 2009). By using Dudh Koshi catchment as the pilot project case study, a systematic road map of work flow process is presented highlighting procedures for prediction and change detection of deglaciation zones combining both machine learning algorithm and remote sensing technologies - for which various methodologies already exists (Frey et al., 2010; Linsbauer et al., 2016).

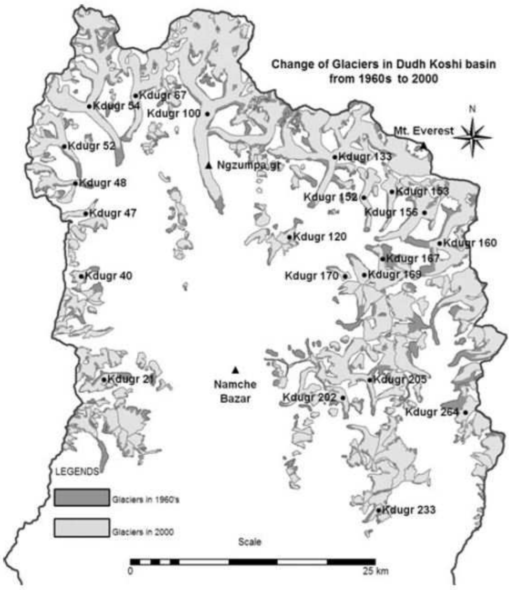


Figure 4.1: **Change in glacier size in Dudh Koshi basin (Bajracharya and Mool, 2009)**

Figure 4.2 shows the Dudh Koshi catchment (inside red box) which lies within the Koshi basin. The Koshi basin is drawn from the outlet point Chatara in Nepal by generating a digital elevation model (DEM) in ArcGIS 10.5 using the National Aeronautics and Space Administration's (NASA) Shuttle Radar Topography Mission (SRTM) 1 Arc-Second data at 30 m resolution. Some parts of the headwater originate from the Tibetan Plateaus in China as seen in figure 4.2. All the data layers such as country boundary, settlement, glacier and glacial lakes inventory to develop this map were obtained from the regional database of the International Center of Integrated Mountain Development.

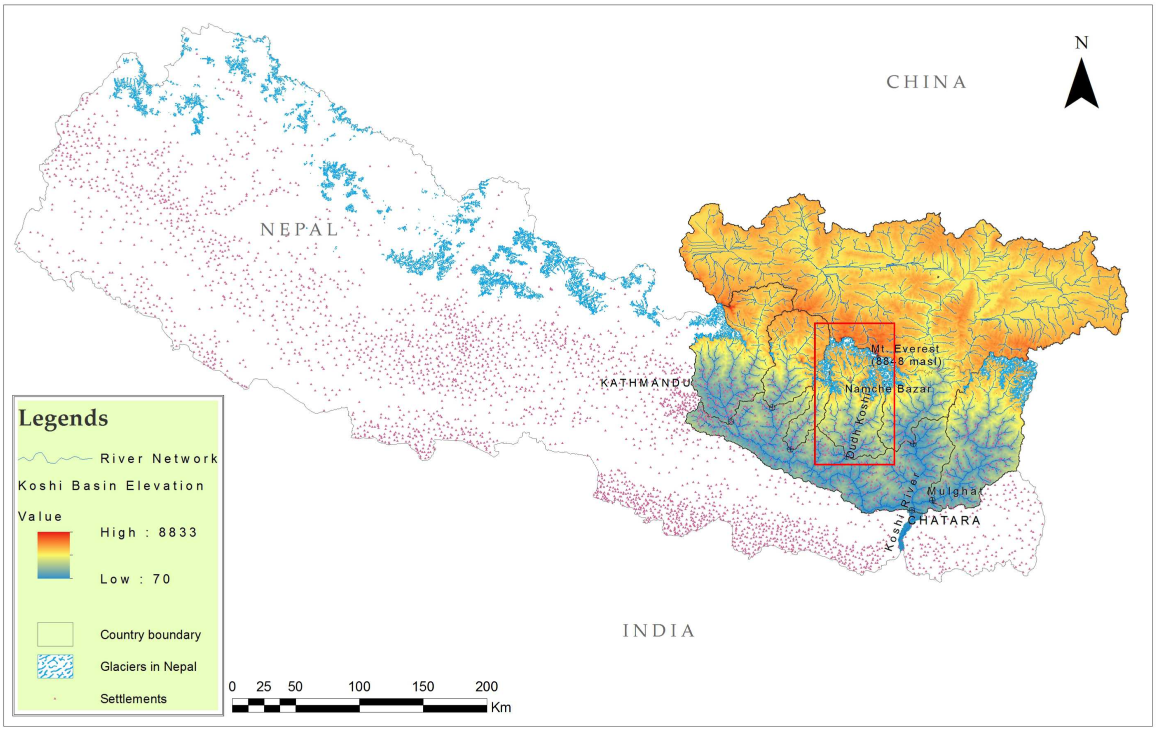


Figure 4.2: **Overview of glaciers in Nepal [Digital Elevation Model developed using SRTM 1 Arc-Second 30m (NASA, NGA) and ICIMOD dataset (country boundary, settlements, glaciers)]**

A boundary condition is set based on elevation to visually assess the glacial lakes. Figure 4.3 shows a map with glacial lakes below 4300 masl while Figure 4.4 shows glacial lakes between 4300 to 5000 masl and above 5000 masl. Figure 4.5 is an enlarged version of Figure 4.4 where the glacial lakes are more pronounced. Two glacial lakes: Dig Tsho at 4364 masl and Tam Pokhari at 4420 masl are marked as potential sites for consideration (Bajracharya and Mool, 2009; Nie et al., 2018) because of its proximity to settlement and their outburst history in the last 35 years. According to ICIMOD's glacial lake inventory data, Dig Tsho burst in 1985 and had an average area of 0.423 km$^2$ while Tam Pokhari - a potential dangerous glacial lake which burst in 1998 had an average area of 0.27 km$^2$ in 2010. The next step is to investigate future landscape evolution which includes overdeepening underneath the glaciers and predict potential lake formation areas based on the works of Linsbauer et al. and Frey et al. as shown in figures 4.6 and 4.7. This will be validated with the results obtained from the machine learning algorithm that will be developed as a part of this project. Field surveys will then be conducted to choose an appropriate and stable location to proceed with the construction of a dam.

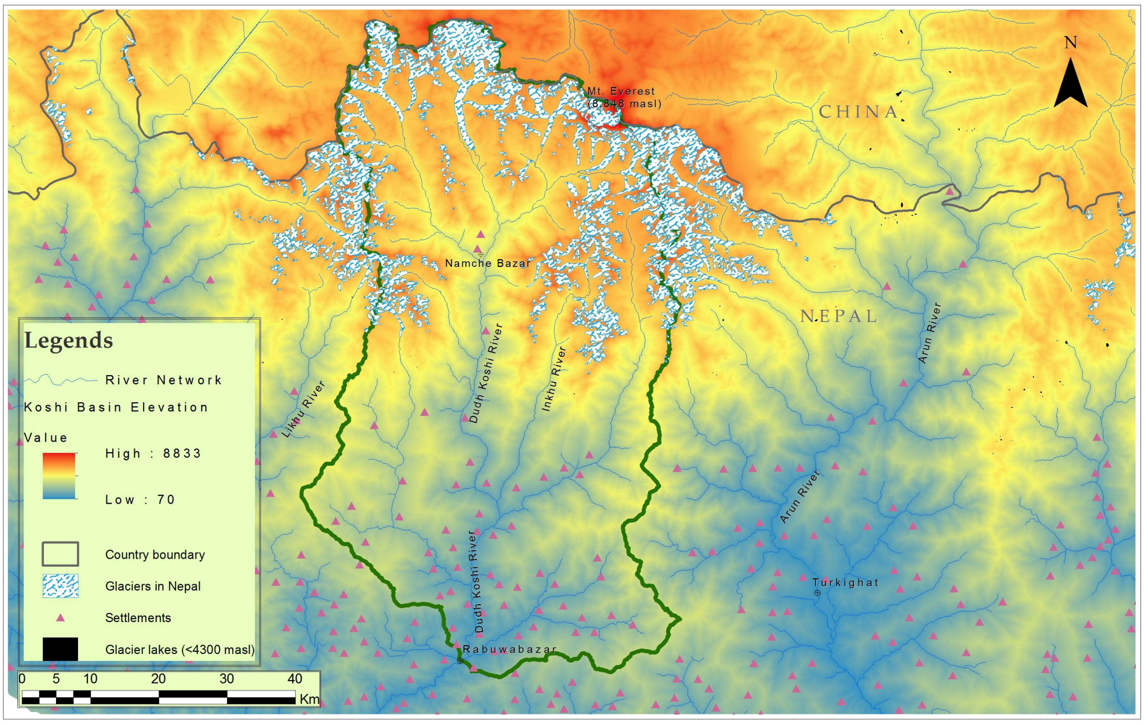


Figure 4.3: **Glaciers in Dudh Koshi below 4300 masl [Digital Elevation Model developed using SRTM 1 Arc-Second 30m (NASA, NGA) and ICIMOD dataset (country boundary, settlements, glaciers, glacial lakes)]**

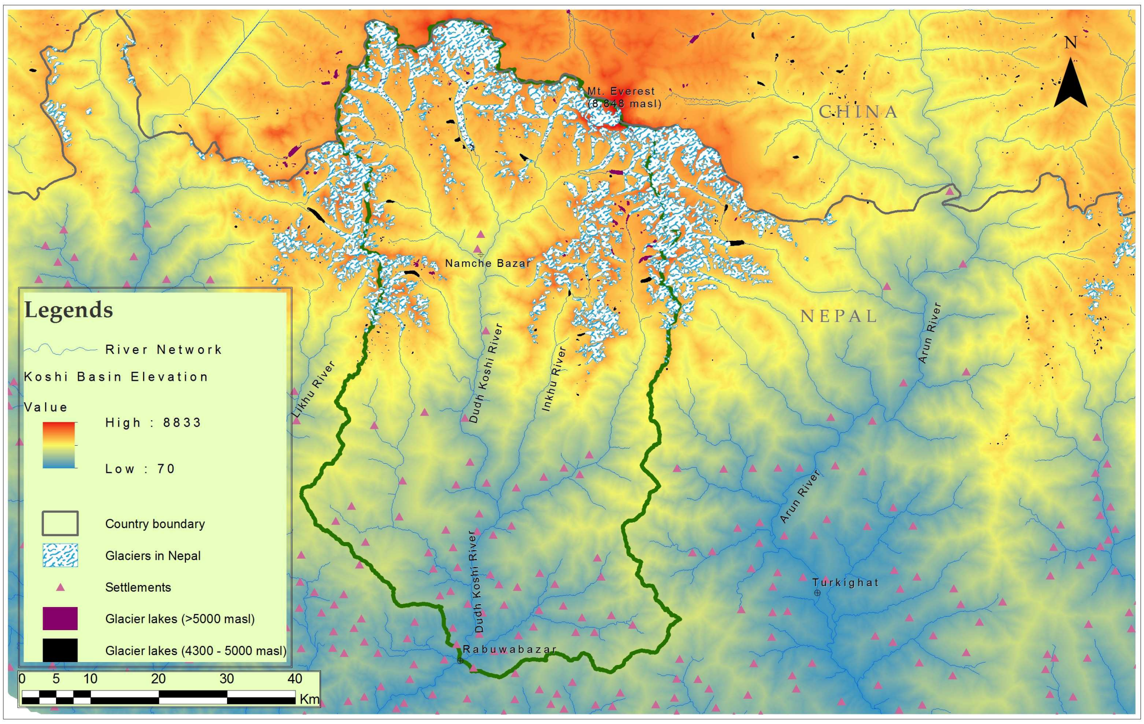


Figure 4.4: **Glaciers in Dudh Koshi above 4300 masl [Digital Elevation Model developed using SRTM 1 Arc-Second 30m (NASA, NGA) and ICIMOD dataset (country boundary, settlements, glaciers, glacial lakes)]**

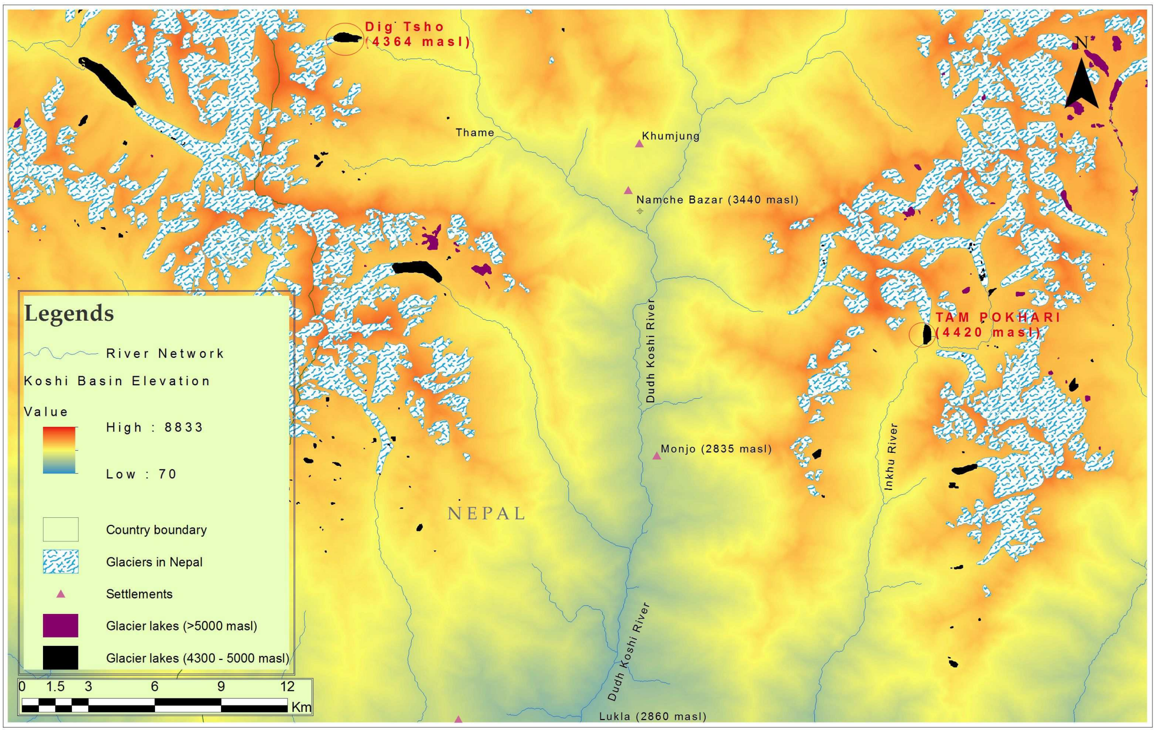


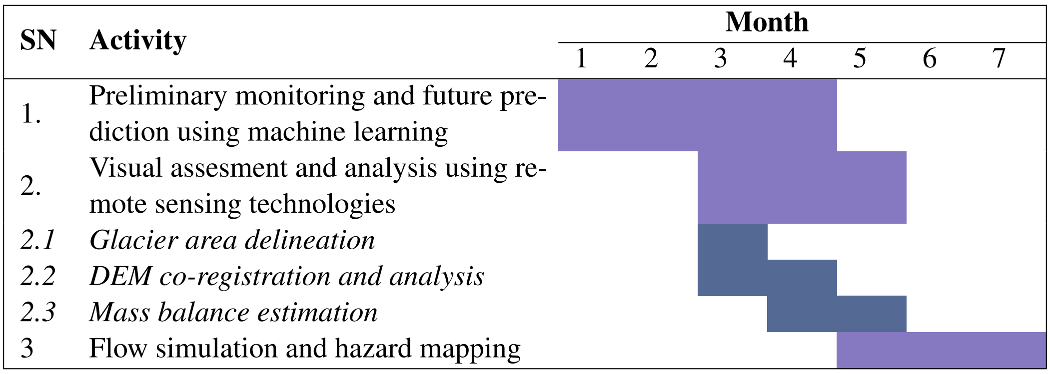
Figure 4.5: **Glaciers in Dudh Koshi above 4300 masl[Digital Elevation Model developed using SRTM 1 Arc-Second 30m (NASA, NGA) and ICIMOD dataset (country boundary, settlements, glaciers, glacial lakes)]**

Figure 4.6: **The glacier inventory (blue outlines) and the modelled overdeepenings (light blue fill) overlay on Google Earth imagery around Everest region (Linsbauer et al., 2016)**

Figure 4.7: **Ice cliffs formation on Khumbu glacier above Dughla shown in 4.6,** ***Photo: P Pradhan***

## 4.2 Time schedule

Figure 4.8 shows a gantt chart that depicts the timeline for the implementation of the proposed methodology. A time frame of about 7 months is proposed in which the research team is expected to accomplish the first few stages of the tasks listed in Section 2.4 and described in Sections 3.1 – 3.3. Only the time schedule until flow simulation and hazard mapping is shown since the construction process itself is beyond the scope of the proposal.



| **SN** | **Activity** | **Month** | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| 1. | Preliminary monitoring and future prediction using machine learning | 🟪 | 🟪 | 🟪 | 🟪 | | | |
| 2. | Visual assesment and analysis using remote sensing technologies | | | 🟪 | 🟪 | 🟪 | | |
| *2.1* | *Glacier area delineation* | | | 🟦 | | | | |
| *2.2* | *DEM co-registration and analysis* | | | 🟦 | 🟦 | | | |
| *2.3* | *Mass balance estimation* | | | | 🟦 | 🟦 | | |
| 3 | Flow simulation and hazard mapping | | | | | 🟪 | 🟪 | 🟪 |

Figure 4.8: Gantt chart showing the time schedule for the proposed methodology

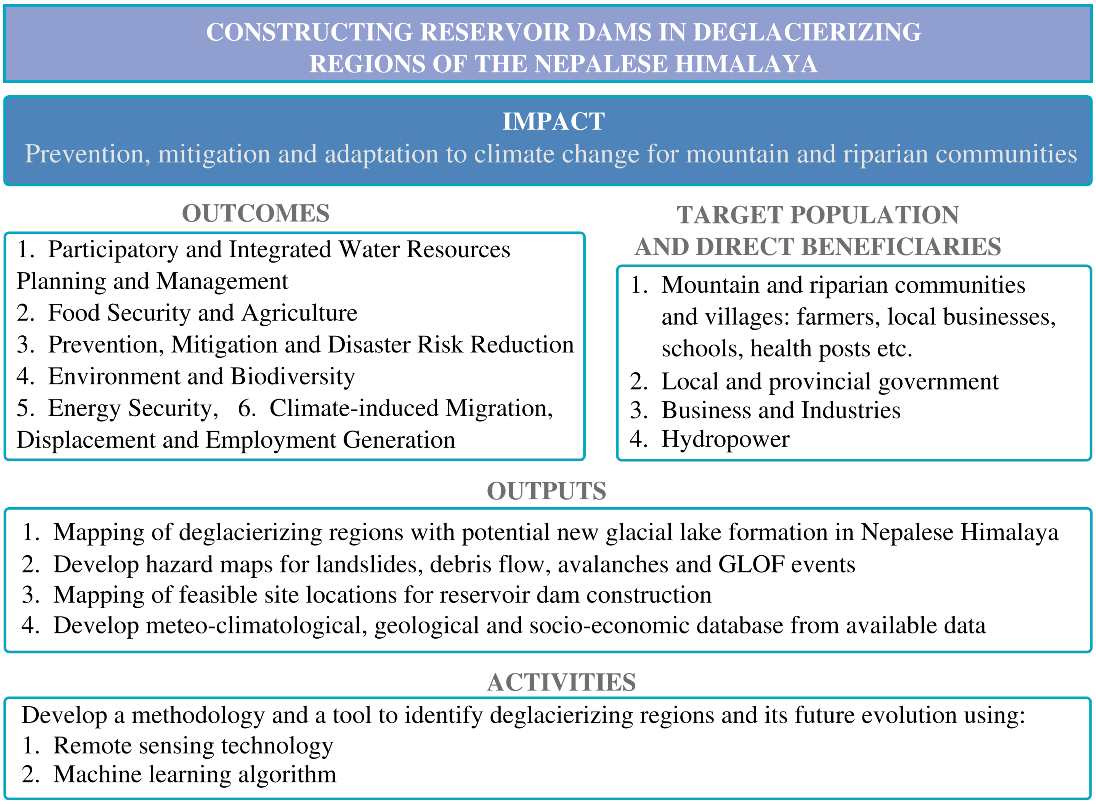
# 5. Expected outputs and outcomes

In his opening remarks to the sessions of the World Economic Forum Water Initiative at the Forum's Annual Meeting in Davos, 29 January 2009, the then United Nations Secretary General Ban Ki-Moon said, *"We have the economic crisis, the food crisis, the energy crisis. To these we can add climate change. All of these crises are still very much with us. They illustrate our world's vulnerability to the shock of diminishing resources. And as you all know only too well, water is very much near the top of the list"*. This is because water is a renewable resource whose need is universal and not just limited to human population but for all species that live in the ecosystem (Biswas, 2004; Steduto et al., 2012). Today the problems arising from water are often interconnected and complex as they intertwined with various development, social, and environmental issues like food and agriculture, energy, industry and employment, education and health, poverty, and ecology and biodiversity (Biswas, 2004). Amongst them, water scarcity is arguably the biggest cross-cutting issue which can stem from uncoordinated planning, inadequate hydraulic infrastructure or physical availability of water itself (Steduto et al., 2012). The other issue is probably 'too much water' which leads to flood related disasters and risks. Both these issues are aggravated by the changing climate. The greatest challenge of our generation now is perhaps to maintain and manage this fine balance between "too little - too much water". Due to its high relevance for ending poverty, and ensuring good health and food security, the Sustainable Development Goals 6 has been dedicated on water - *to ensure availability and sustainable management of water and sanitation for all* (Smith and Clausen, 2018). By constructing a reservoir dam or even a network of such reservoir dams, the issue of water scarcity and water stress could be addressed, and the risk of flooding and debris flow in the catchment could be significantly reduced while ensuring the sustainable livelihood of the downstream communities and addressing the concerns of the food, water and energy security nexus.

The methodology mentioned in Chapter 3 acts as a precursor to pave the way for stage 2 - 6 (Section 2.4). When the reservoir dam is thus finally built, it could lead to the following output and outcomes (benefits) which is also illustrated in Figure 5.1:

## 5.1 Participatory and integrated water resources planning and management

The concept of macro and meso scale dam construction for integrated water resources management has been around for more than half a century. Despite their appeal, there are not many success stories



CONSTRUCTING RESERVOIR DAMS IN DEGLACIERIZING REGIONS OF THE NEPALESE HIMALAYA

IMPACT

Prevention, mitigation and adaptation to climate change for mountain and riparian communities

OUTCOMES

1. Participatory and Integrated Water Resources Planning and Management
2. Food Security and Agriculture
3. Prevention, Mitigation and Disaster Risk Reduction
4. Environment and Biodiversity
5. Energy Security,
6. Climate-induced Migration, Displacement and Employment Generation

TARGET POPULATION AND DIRECT BENEFICIARIES

1. Mountain and riparian communities and villages: farmers, local businesses, schools, health posts etc.
2. Local and provincial government
3. Business and Industries
4. Hydropower

OUTPUTS

1. Mapping of deglacierizing regions with potential new glacial lake formation in Nepalese Himalaya
2. Develop hazard maps for landslides, debris flow, avalanches and GLOF events
3. Mapping of feasible site locations for reservoir dam construction
4. Develop meteo-climatological, geological and socio-economic database from available data

ACTIVITIES

Develop a methodology and a tool to identify deglacierizing regions and its future evolution using:

1. Remote sensing technology
2. Machine learning algorithm

Figure 5.1: **Expected outputs and outcomes of the project**

because of their inability to address complex problems of a real world that is heterogeneous with different cultures, social norms, physical attributes, management capacities, institution arrangements and system of governance (Biswas, 2004). Therefore, for the management of the reservoir dam, the Participatory and Integrated Planning (PIP) procedure based on the methodology developed by Soncini-Sessa and Castelletti ((Soncini-Sessa et al., 2007a,b; Castelletti and Soncini-Sessa, 2006)) and multi-criteria decision analysis are proposed. They take into account attributes of other disciplines such as decision making theory, system analysis, hydrology, ecology and sociology amongst many.

There are different multi-objective optimization techniques to design reservoir operating policies that give Pareto-optimal trade-offs between multiple stakeholders and their respective interests (Bizzi et al., 2012). However, even after meeting the requirements for minimum environmental flow (MEF), ecological degradation in downstream areas cannot be avoided at any given hydrological alteration because a constant threshold value is set for an entire year which cannot take account of the hydrological processes (Bizzi et al., 2012). To address this issue, monthly magnitude of the flow, magnitude, duration and timing of annual extreme water conditions, frequency and duration of high and low pulses and the rate and frequency of water condition changes should be considered such that the former runoff regime are maintained (Richter et al., 1996) while building the dam in high mountain headwater catchment.

### Participatory and Integrated Planning (PIP) procedure

For operational planning and management of the reservoir dam, the Participatory and Integrated Planning (PIP) procedure based on the methodology developed by Soncini-Sessa and Castelletti is proposed (Soncini-Sessa et al., 2007a,b; Castelletti and Soncini-Sessa, 2006). The PIP procedure comprises of 9 phases as shown in Figure 5.2. It starts with the identification of goals of the planning activity and ends with a negotiation process among the stakeholders, all of whom are presented with a set of alternatives to be submitted to their respective decision maker/s for the final political decision (Castelletti and Soncini-

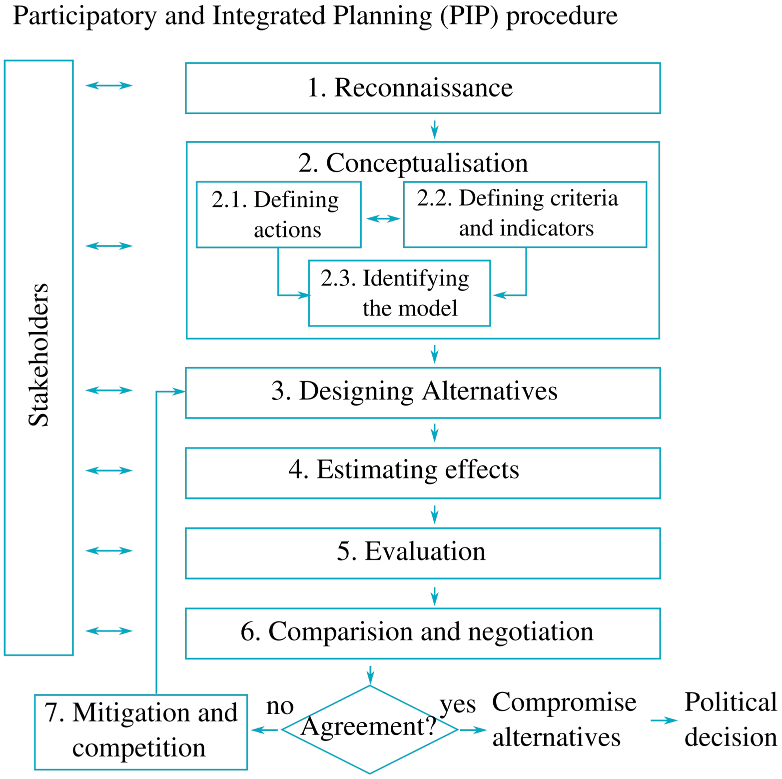


Figure 5.2: **Flowchart for Participatory and Integrated Planning Procedure (Castelletti and Soncini-Sessa, 2006)**

Sessa, 2006). At every step in PIP, there is an engagement of human beings who make decisions which are subjective depending on the compromises that they make, to take actions which are suitable for them and their interests (Castelletti and Soncini-Sessa, 2006). It is therefore a recursive procedure where in the development of a step, the social learning process implies that something in the previous step has to be modified as well. The social learning process is ensured by active and public participation of the stakeholders thus creating an interactive process of social learning even among the stakeholders.

### Multi-Criteria Decision Analysis (MCDA)

In addition to PIP procedure, a multi-criteria decision analysis will also be performed, the outline of which is shown in Figure 5.3. In this procedure, the criteria and interests of the stakeholders (for example, in terms of environmental impacts, cost, public acceptance, peripheral features, ability to meet future demand, etc.) will be identified. For technical decision making, experts with appropriate background will be consulted particularly when selecting the site based on glacier geometry, site stability, project feasibility, access to site (proximity), and impact to watershed. These criteria and interests will be rated using an ordinal scale (on a 10-point scale) depending on whether or not an alternative meets the interest. For each interest, an appropriate weight will also be assigned based on the recommendations of the experts. Finally, the score for each interest will be multiplied by its corresponding weight to calculate its final score. Summing the score yields the preferred site for a stakeholder. Even if a unanimous decision is not reached, MCDA is expected to identify the most appropriate locations from a range of possible alternatives.

## 5.2 Food security and agriculture

By defining the reservoir operating policy for integrated water resources management using PIP procedure, the major issues of water availability, allocation and management for agriculture and irrigation sector can be addressed. This is particularly important for the Koshi River Basin under concern since agriculture

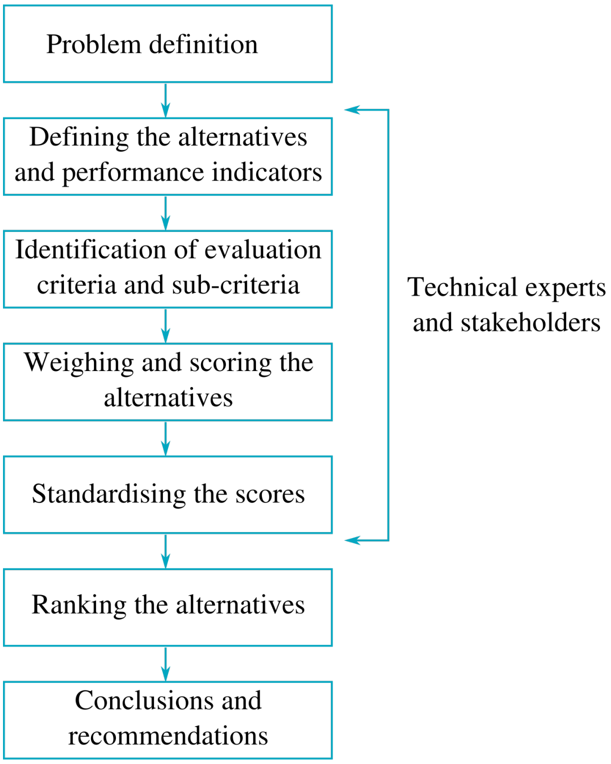


Figure 5.3: **Overview of the proposed MCDA approach for selection of appropriate site for reservoir construction**

(arable farming and animal husbandry) and fishery is a widely practised occupation in this region. This, in turn, is driven by the glacier-fed rivers of the basin. In the Dudh Koshi Basin, farmers mostly rely upon the rain-fed systems and irrigation via multi-use micro-hydro plants, particularly at higher elevations where maize, millet and potatoes are grown, and livestock is raised (Bartlett et al., 2010). In the lower elevations, irrigation practices are also prevalent for rice production in terrace farming (Bartlett et al., 2010). However, climate change impacts on the Koshi Basin on the whole have shown decline in agricultural production, increase in fallow lands, sedimentation of cultivable land, with increasing number of people shifting towards non-agricultural activities (Bastakoti et al., 2017). Regulated supply of water in the rivers may help mitigate the limitations of agricultural water availability and increase in drought events. This provides another incentive to construct a dam in deglaciarized region upstream to secure water downstream. This further identifies farmers as key stakeholders in the PIP approach as discussed in Section 5.1.

## 5.3 Prevention, mitigation and disaster risk reduction

Dam has an inherent function of being used for flood protection by reducing peak flows. It can also be used to control sediment yield and debris as well as nutrient load. In downstream areas, it will reduce the flood disaster risk and also help to supply regular flow of water during dry period of drought, thus increasing the resilience of the communities. Building a dam in deglaciarized areas in high mountain environment where there is a potential for lake formation help mitigate the GLOF threat by replacing a loosely formed moraine dam with a concrete structure. At the same time, it is also an adaptation strategy to water resource management to cope with the adverse impacts of climate change in multiple sectors downstream where water is needed such as agriculture and irrigation, water supply, environment and many more. Also by building a dam in high mountains, one could prevent the loss that is endured due to evaporation in a reservoir dam downstream having large water surface areas.

## 5.4 Environment and biodiversity

Most opposition towards dam come due to environmental concerns such as biodiversity loss or ’drying up of rivers’, and socio-economic and environmental cost arising from inundation of river banks while filling up the storage of the dam (Shah and Kumar, 2008). Sometimes the socio-economic and environmental cost due to displacement and irreversible damage to the ecosystem and natural habitat far exceeds the investment and benefit of building the dam. However, if the dam is built in high mountain headwater where new landscape is evolving, such aspects will not be as significant compared to dams in downstream locations.

## 5.5 Energy security

Several hydropower projects are reliant upon the flow of the glacier-fed rivers in Nepal. In the Koshi River Basin, 11 potential sites at mid-stream locations were identified by Japan International Cooperation Agency (JICA) for hydropower generation and water storage (JICA, 1985, 2014). The Dudh Koshi catchment alone bears a potential of 118 MW (Chinnasamy et al., 2015). Thus, energy security is an important sector in this Basin that can potentially be affected due to the alterations in the flow of the rivers due to climate change. Furthermore, GLOF pose a great threat to the hydropower plants and infrastructures downstream. As such, a reservoir of an appropriate size in the appropriate location upstream not only ensures energy production but it also protects the infrastructures from potential damages and losses.

## 5.6 Climate-induced migration, displacement and employment generation

An important consequence of the climate change on Dudh Koshi River Basin is the migration of farmers towards other income-generating opportunities such as business and tourism, as briefly described in Section 5.2. While such shift from agriculture to other livelihoods is to a certain extent a global phenomenon, the concern in the region is that access by land transportation is poor and the food supply is reliant upon the local production. This raises a concern with respect to the food security in the region. The displacement of the local people to other places is another major concern since climate change induced uncertainties have adversely affected traditional agricultural practices in the region. Another key factor for migration of people is due to increasing risks of GLOFs that force people to relocate elsewhere. As such, construction of reservoirs may help address this issue by not only securing water throughout the year, but also by mitigating the risks of GLOFs.

# 6. Conclusions

Since 2014, there has been a string of record hot years and 2017 was not an exception according to the most recently released report "State of the climate in 2017" (Blunden and G. Hartfield, 2018). According to this report, 2017 was the $3^{rd}$ warmest year on record with the levels of greenhouse gases the highest on record, sea level rise about 7.7 cm higher than the 1993 mean, Arctic maximum sea ice coverage falling to a record low in 38 year record along with the Antarctic sea ice coverage (Blunden and G. Hartfield, 2018). In light of these emerging evidences, it is likely that deglaciation processes will continue unabated in the high altitudes mountainous regions. Once the glaciers disappear or shrink, the hydrological regimes of the downstream catchments are bound to change in future. This will have a huge implication on all flora, fauna and human population living downstream who depend on this source of water, particularly during dry summer periods. The growing human population and competing use of water will only further aggravate water stress in the future (Vörösmarty et al., 2000).

The deglaciation processes from the retreating glaciers will leave behind a new fragile landscape of bare bedrocks and loose debris. While such new landscape evolution could pose potential new risks and challenges, they could also open new frontiers of opportunities. One way to exploit such opportunities which has been discussed here is to build a dam such that it will resuscitate the hydrological function of glaciers, mitigate the risk of disasters such as GLOF, debris flow and avalanches. Furthermore, it will help develop resilience to climate change across the water-food-energy nexus which is critical in addressing the sustainable development agenda to alleviate poverty and hunger (Ozturk, 2015). This is a bold and rather provocative approach as "dams or no dams" is a controversial topic around the world for their negative social and environmental costs (Shah and Kumar, 2008; Farinotti et al., 2016). In fact, there is a Nigerian proverb, "In the moment of crisis the wise build bridges and the foolish build dams". While there are huge risks, a dam can also transform the same risks into rewards. Controversial issues around dams arise from displacement and resettlement of local and indigenous communities, inundation of riverine freshwater habitat and ecosystems and environmental impacts such as "drying up of rivers", loss of natural variability, sediment trapping and evaporation losses (Shah and Kumar, 2008) and one may argue these costs outweigh the benefits. However, such negative issues arise when dams are conventionally built in the middle-stream or downstream of the catchment but not at the origin of the river in high mountains itself. Furthermore, they also seldom include the participatory approach in planning and operational policy management of the reservoir which is proposed here.

The idea of building dams in high mountains should be explored, as dams can mimic the hydrological function of a glacier when they disappear due to climate change. Moreover, the negative environmental and social costs of dams in high mountains are significantly lower than conventional dams at lower altitude. Having said this, mountains are fragile environment and usually lie on seismically active zones. Therefore, any structural construction in these areas require a great engineering feat based on good science and sophisticated technology along with cooperation and collaboration from many stakeholders. This proposal does not delve into how to construct such technical structural designs as it is beyond the temporal and financial scope of this proposal, and one that requires specialized skill sets in civil engineering and engineering geology, as well as information from various field surveys. For the same reasons, one cannot propose a specific site or specify whether the reservoir dam will replace a glacial lake or just be built in a deglaciated space. At best, the idea is to replace a glacial lake, and if not, build it in a deglaciated region. Nevertheless, their hydrological function remains the same. Hence, in this proposal we provide a technical basis to move into that direction. By using Dudh Koshi catchment as a pilot project case study, a systematic roadmap to accomplish such goals are plotted. It highlights procedures for prediction and change detection of deglaciation zones by developing machine learning algorithm based on satellite imageries and validating it with analysis based on remote sensing technologies, for which various methodologies already exists. A novel and new approach proposed here is the combined use of machine learning algorithms with remote sensing technologies for change detection and evolution of deglaciation regions from which a spatial map with different spectrum of risk and hazard areas is generated to locate the most feasible site for the construction of these reservoir dams.

In today's world where problems are inherently multi-faceted, engineers with a passion for sustainable development, and development practitioners with a knowledge of technology can contribute more innovative solutions than engineers and practitioners alone. This project aspires to be such an interdisciplinary development project and this proposal explores new frontiers, driven by challenges of the contemporary world in times of climate change.

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