Temporal Analysis of Potentially Dangerous Glacial Lakes (PDGLs) in Nepal: Assessing the Seasonal Glacial Melt Inflow into the Thulagi Glacier Lake (Dona Lake)

Submitted in partial fulfillment of the requirements for the

Bachelor's Degree in Environmental Science

By;

Umanga Pandit (026378-19)

Swikrit Subedi (026402-19)

Department of Environmental Science and Engineering

School of Science

Kathmandu University

Dhulikhel, Kavre, Nepal

26 May 2024

CERTIFICATION

This Project Report entitled "**Temporal Analysis of Potentially Dangerous Glacial Lakes (PDGLs) in Nepal: Assessing the Seasonal Glacial Melt inflow into the Thulagi Glacier Lake (Dona Lake)**" is carried out under my supervision for the specified period satisfactorily, and is hereby certified as an original work done by **Umanga Pandit** and **Swikrit Subedi** in partial fulfillment of the requirements for the Bachelor's degree in Environmental Science, Kathmandu University, Dhulikhel, Nepal.

Approved By:

....

Supervisor
Dr. Nani Raut, Assistant Professor
Department of Environmental Science and Engineering, Kathmandu University

Date: 1 June, 2024

....

Co-Supervisor
Er. Nirakar Jung Thapa
Department of Hydrology and Meteorology, Ministry of Energy, Water Resource and Irrigation, Government of Nepal

Date: 1 June, 2024

I hereby declare that these candidates qualify to submit this work as a Bachelor's Project Report.

....

Head of Department
Dr. Kumud Raj Kafle
Department of Environmental Science and Engineering
Kathmandu University

Date: 1 June, 2024

....

External Examiner

Date: 1 June, 2024

DECLARATION

We, **Umanga Pandit** and **Swikrit Subedi**, hereby declare that the work presented here is genuine work done originally by us, except where, stated otherwise by reference or acknowledgment, and has not been published or submitted elsewhere for the requirement of a degree program. Any literature, data, or works done by others and cited within this report have been given due acknowledgment and listed in the reference section.

…………………………………………

Umanga Pandit
Department of Environmental Science and Engineering
Kathmandu University

Date: June 1, 2024

…………………………………………

Swikrit Subedi
Department of Environmental Science and Engineering
Kathmandu University

Date: June 1, 2024

ACKNOWLEDGEMENT

We would like to convey our sincere gratitude to our supervisors, **Asst. Prof. Dr. Nani Raut** and **Er. Nirakar Jung Thapa** for their invaluable guidance, support, and direction throughout this project. Their beneficial suggestions and support motivated us to accomplish our study. In addition, we would like to acknowledge **Innovative Water & Environmental Solutions (IWES)** for their considerable assistance and support throughout our project.

We are grateful to the **Department of Environmental Science and Engineering, Kathmandu University** for allowing us to carry out our project. We are extremely thankful to **Associate Professor, Dr. Smriti Gurung** for her input, encouragement, invaluable contributions, and coordination during the semester. We are grateful to all those who have contributed directly or indirectly to completing our project.

Umanga Pandit

Swikrit Subedi

B. Sc. Environmental Science

Kathmandu University, Dhulikhel, Kavre

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

DEM - Digital Elevation Model

DHM - Department of Hydrology and Meteorology

GLIMS - Global Land Ice Measurement from Space

GLOF - Glacier Lake Outburst Flood

HKH - Hindu Kush Himalayas

ICIMOD - International Center for Integrated Mountain Development

LAP - Local Adaptation Plan

MODIS - Moderate Resolution Imaging Spectroradiometer

NAP- National Adaptation Plan

NDWI - Normalized Difference Water Index

NIR - Near Infrared

OLI - Operational Land Imager

PDGLs - Potentially Dangerous Glacial Lakes

TAR - Tibet Autonomous Region

TIRS - Thermal Infrared Sensor

TM - Thematic Mapper

UAV - Unmanned Aerial Vehicle

USGS - United States Geological Survey

SYMBOLS AND UNITS

a.s.l - Above Sea Level

km3 - Cubic Kilometer

m3 - Cubic Meter

°C - Degree Celsius

Gt - Gigatonne

km - Kilometer

m3/s - Meter Cube Per Second

$m.a^{-1}$ - Meters Per Year

m.w.e. - Meters Water Equivalent

mm - Millimeter

sq.km - Square Kilometer

ABSTRACT

Climate change has triggered an era of global boiling, with projections indicating a trajectory exceeding 2°C during the next two decades. This rise in temperature has accelerated the alteration of Earth's cryosphere, including the glaciers in Nepal, which are retreating at varying rates. The rapid expansion and formation of glacial lakes due to glacial retreat are potentially hazardous for their associated risk from Glacial Lake Outburst Floods (GLOFs). This study investigates decadal variations in the extent of 21 Potentially Dangerous Glacial Lakes (PDGLs) of Nepal using remote sensing data from Landsat satellites. The findings displayed an overall rising trend in 14 of the 21 glacial lakes, with an average decadal increase of 0.6 - 48.78% of the lake area. Lakes like Imja, Lower Barun, Thulagi, Tsho Rolpa, Chamlang, and Lumding Tsho are expanding more rapidly than others. Lakes GL087596E27705N, GL082673E29802N, and GL086977E27711N have increased substantially as well. Lake GL087945E27781N however, shows a substantial reduction. The remaining seven lakes have maintained a virtually stable area since the 1980s. Among the PDGLs, only the Dona Lake lies within the western region of Nepal, where limited studies have been conducted compared to the Khumbu region in the central region. We utilized the MODSNOW tool to assess the glacial melt patterns of Dona Lake. The MODSNOW-modeled glacier melt shows growing discharge rates throughout the monsoon season, followed by post-monsoon and pre-monsoon periods, indicating variations in melt dynamics within the Marsyangdi river basin due to characteristics of the source glacier, and climatic variations responsible for changes in the Indian Monsoon and Westerlies. The findings stress the need for a deeper understanding of glacier dynamics in the Nepalese Himalayas, emphasizing the importance of adaptive methods for mitigating risks and ensuring the resilience of vulnerable communities and ecosystems.

Keywords: Potentially Dangerous Glacial Lakes (PDGLs); Glacier Lakes; Glacier Retreat; Dona Lake; Glacial Lake Outburst Flood (GLOF); Glacial Melt

CHAPTER I: INTRODUCTION

1.1 Background

Climate change refers to long-term changes in Earth's average global temperature and weather patterns (NASA, 2023). Anthropogenic activities, notably the burning of fossil fuels, have become the primary driver of these changes, resulting in approximately 1.1°C of global warming since the late 19th century. Projections suggest a trajectory that may exceed 1.5°C warming in the next two decades (Fischer & Knutti, 2015; IPCC, 2021). The rise in global temperatures has become synonymous with the transformation of Earth's local, regional, and global climates, progressing at a pace surpassing natural climate fluctuations throughout Earth's history (WBG, 2021). This has led to significant alteration in the cryosphere across numerous regions worldwide (Paul et al., 2002; Nie et al., 2010). For instance, the Hindu Kush Himalayas (HKH) region is expected to see a greater increase in surface mean temperature by the end of the twenty-first century than the global average. In this region, a 1.5°C increase in global temperature would correspond to a minimum of 2.1°C (Kraaijenbrink et al., 2017).

Furthermore, mountainous and highland regions are susceptible to local climatic shifts. Heightened temperature trends have led to significant glacier retreat and thinning in these areas, as evidenced by the rapid melting and shrinking of numerous Himalayan glaciers since the 1980s (Bolch et al., 2012; Bajracharya et al., 2020). The gradual reduction in glacier extent has far-reaching consequences for the region's runoff patterns, water reserves, and hydrological dynamics (Immerzeel et al., 2010; Yao et al, 2010). This decline in glacial capacity to store water seasonally not only heightens the risk of natural disasters but also jeopardizes the lives of millions of people who reside in the high mountains of Asia, posing intricate adaptation challenges for policymakers, water management professionals, and local communities that rely on mountainous water resources. (Kraaijenbrink et al., 2017).

In the context of Nepal, where the Himalayan range stretches from west to east, spanning an entire 800 km length within the southern lap of the 2400-km-long Himalayan Arc, the glaciers are found to be exhibiting heterogeneous shrinkage in the area (ranging from -1 to -5 square kilometers per year), possessing negative mass balance (ranging from -0.3 to -0.8 meters water equivalent per year). Over the past three decades, the country has experienced a significant decline in its ice reserves, totaling approximately 128.8 cubic kilometers, contributing to a rise in sea levels of approximately 0.32 millimeters (Le Fort, 1975). Additionally, there has been an accelerated formation and expansion of glacial lakes with surface areas increasing by approximately 0.83% annually (Wang et al., 2011; Bajracharya et al., 2020; Khadka et al., 2023). The research carried out in the Koshi, Gandaki, and Karnali basins by the International Centre for Integrated Mountain Development (ICIMOD) provides intriguing insights into the composition of the glacial lakes in the region. Among the diverse types of glacial lakes observed, moraine-dammed lakes emerge as the most predominant form, accounting for around 55% of the 2,003 lakes that have been studied. Following closely are bedrock-dammed lakes, comprising 35% of the examined lakes (1,255) (Bajracharya et al., 2020).

Glacial lakes are an economic asset since they function as freshwater reservoirs, generate hydroelectric power, and allow for improved water flow regulation (Komori, 2008; Shugar et al., 2020). However, the process of glacial melt elevates hydrostatic pressure, causing structurally weak and unstable dams to fail abruptly (Bajracharya et al., 2020). This might result in a sudden high discharge of debris and water in a few hours, leading to catastrophic floods that cause thousands of fatalities and have serious consequences for downstream communities, infrastructure, and long-term economic development (Richardson & Reynolds, 2000; Benn et al., 2012). These GLOFs, in particular, arise primarily from moraine-dammed glacier lakes since they are generally composed of loose, coarse material with minimal cementing content. This composition facilitates easy erosion, rendering lakes with moraines of this material vulnerable to GLOFs (Bajracharya et al., 2020).

1.2 Rationale

Recent studies in Nepal reveal a rise in maximum temperature at a rate of 0.04 °C per year over the past four decades, exceeding the global mean increase (IPCC, 2018; Karki et al., 2020; Poudel et al., 2020). Additionally, data sourced from the Department of Hydrology and Meteorology (DHM) highlights a yearly decrease of 1.46 millimeters (mm) in rainfall in the Higher Himalayas of Nepal between 1971 and 2014 (DHM, 2017). These shifts are attributed to the effects of Climate Change, which has led to increasingly variable and unpredictable rainfall patterns, demonstrating uneven moisture distribution at a spatial scale (Pandey, 2016; Putnam & Broecker, 2017; Zhang et al., 2021; Yadav et al., 2024).

As Nepalese glaciers and lakes respond dynamically to global warming, the consequent glacier melt increases the number and area of moraine-dammed glacier lakes (Bajracharya et al., 2011). This in turn enhances the risk of GLOFs and avalanches (Linsbauer et al., 2016; Ding et al., 2019; Pandey et al., 2021), posing direct and indirect threats to the socioecology of downstream communities (Kulkarni et al., 2021; Dubey et al., 2024)

According to ICIMOD (Bajracharya et al., 2020), 21 of the 47 identified PDGLs are within the Gandaki, Karnali, and Koshi River Basins inside the Nepalese boundary, posing a considerable risk of GLOFs. The report compiles area data for a single year to determine flood risk classifications associated with these lakes. However, further research is warranted to understand the evolution of these lakes over time. Our study addresses this by systematically quantifying and visually representing the variations in the area of these 21 glacial lakes since the 1970s with remote sensing, thereby providing insights into the temporal dynamics of these glacial lakes, and enhancing our understanding of their growth and associated risks.

Dona Lake seeks special attention due to its designation as a Rank I PDGL - a category of lakes that have a high possibility of expansion, are dammed by loose moraine material, and can experience natural hazards like landslides and avalanches in their catchment that could impact the lake and the dam (Kargel et al., 2015). Hence it poses a threat from catastrophic flooding with peak flows ranging from 1399 to 5334 m3/s (Maskey et al., 2020). Its downstream impacts extend to Tal village in the Dharapani area where disruption in tourism, trade, and hydropower plants amounts to a loss of USD 406.73 million in case of a GLOF (Khanal et al., 2015). The associated socio-economic vulnerabilities underscore the urgency for robust research and risk management strategies, especially considering the marginalized Indigenous populations (90%) residing in GLOF-risk areas (Mool et al., 2011). Besides, the lake is much less studied in comparison to other lakes of concern like Imja and Lower Barun, which highlights the need for further investigation.

1.3 Research Questions

In this study, we aimed to analyze the decadal changes in PDGLs within the Nepalese boundary by answering the following research questions:

1. What is the extent of decadal changes in the area of glacial lakes within the Nepalese Himalayas?
2. What is the seasonal average glacial melt inflow into Dona Lake?

1.4 Objectives

The main objective of this research is to analyze the decadal changes in PDGLs within the Nepalese boundary. Specific objectives are as follows:

1. To map and quantify the decadal changes in the area of PDGLs within the Nepalese Himalayas.
2. To simulate the seasonal average glacial melt inflow into the Dona Lake using a degree day model.

1.5 Limitations of the Study

The limitations of our study are;

- The study is confined to using Landsat satellite imagery, leading to potential limitations in verifying the accuracy of glacial lake areas through on-site visits.
- Due to varying levels of data availability caused by cloud cover obstructing the satellite imagery, it was not feasible to maintain uniform intervals for data collection across all glacial lakes.
- The area of glacial lakes could be subject to ambiguous deviations due to local fluctuations in weather patterns and human errors while manually smoothening the polygon to align with the lake boundaries.
- Due to the unavailability of rainfall data near Dona Lake and missing data in the Chame weather station, we opted for precipitation data from the entire Marsyangdi Basin.

CHAPTER II: LITERATURE REVIEW

2.1 Global Status of Glaciers and Glacial Landforms

As global temperatures soar over higher altitudes, glaciers retreat, expanding the number of glacial lakes and affecting the seasonal discharge of underlying river basins (Pepin et al., 2015; Moyer et al., 2016). An analysis of satellite images reveals that the total volume of glacial lakes worldwide increased by approximately 48% between 1990 and 2018 (Shugar et al., 2020). While all regions are witnessing significant loss of glacier mass, the changes in annual runoff vary spatially (Huss & Hock, 2018; Gusev et al., 2019). This variability depends on the balance between increased melting and the reduction of glacier reservoirs due to retreat and shrinkage. For instance, regions like Arctic Canada North, the Russian Arctic, and Greenland are experiencing an increase in runoff totals, whereas places like Iceland, Svalbard, and Switzerland are seeing a decrease in both annual runoff and peak flow (Bliss et al., 2014; Rahman et al., 2015).

Using modern satellite imagery and airborne lidar, Aðalgeirsdóttir et al (2020) monitored 98.7% of Iceland's glacier-covered areas (in 2019) to monitor mass change since the end of the Little Ice Age. A total mass change of −540 ± 130 Gt was seen during the study period (1890/91 to 2018/19), half of it occurring from 1994/95 to 2018/19. Icelandic studies show significant increases in the rate of terminus retreat and lake expansion due to rising air temperatures, although spatial complexities are driven by glacier-specific factors (Staines et al., 2015; Dell et al., 2019).

In the European Alps, a temperature rise of 0.5–1.2 °C has resulted in a decrease of 25–50% in the occurrence of floods having a return period of 10 years or more (Wilhelm et al., 2022). This finding is backed by Dokulil et al (2010) who suggest concerns about up to a 50% reduction in summer rainfall in some areas, as average summer temperatures in parts of Central Europe are projected to increase by as much as 6°C by 2100. Likewise, the Rhone River displays a decline in peak flow during summer and an earlier onset of melt-driven peak flow due to a changing climate (Rahman et al., 2015).

Across the Atlantic, most Hydrometric stations show an increasing trend of annual discharge in Canadian rivers due to Climate and anthropogenic factors, differences among ecoregions, and altered inter-annual distribution of precipitation (Li et al., 2016; Hulley et al., 2019). Between 1984-1988 and 2016-2019, ice-marginal lakes in Alaska and northwest Canada increased in number (+183 lakes, 38 % increase) and area (+483 sq. km, 59 % increase). Moraine-dammed lakes in particular increased at a rate higher than the average, by +479 sq. km, an 87 % increase for number and area, respectively (Rick et al., 2022).

Down south, the impact of increased temperature has been observed in the glaciers and permafrost areas of South America, particularly the Andean ranges, Patagonia, Tierra del Fuego, and the Antarctic Peninsula at least since 1978 and, particularly in the last decade of the twentieth century (Gonzalez & Fortuny, 2018; Etourneau et al., 2019). The most noticeable impacts are the fast glacier margin recession, the thinning of the ice cover, the elevation of the regional snowline, and the reduction of Andean areas under permafrost conditions (Rabassa, 2009). The Chilean Patagonia has been characterized by some of the fastest glacial retreats worldwide (Boyd et al., 2008; Lopez et al., 2010) and increased GLOF events (Casassa et al., 2010). Research in the Central Andes, Northern Patagonia, and Southern Patagonia reveals that glacial lakes across the study area have significantly increased in number (43%) in recent years (1986-2016) with some sub-regional variations in lake growth and emergence. Such changes equate to a glacial lake water volume increase of 65 km3 during the 30-year observation period (Wilson et al., 2018). Consequently, flood discharge estimates are larger than since the 1989 GLOF event in the Valle Soler, as determined by satellite-derived DEM and UAV imagery (Burton et al., 2020).

2.2 Status of Glaciers and Glacial Landforms in the HKH Region

In the HKH region, often referred to as the water towers of Asia, glacier contributions to streamflow increase by roughly 50% with a 1 Kelvin increase in temperature (Shea and Immerzeel, 2016; Huettmann & Regmi, 2020). As temperatures rise, rivers are expected to receive decreasing glacier contributions (up to 90%) by the end of the 21st century (Bolch et al., 2019).

Li et al (2022) analyzed multitemporal Landsat images taken from 1990 to 2020, to understand spatial distribution and evolution of glacial lakes. From 5835 (664.84 ± 89.72 sq. km) glacial lakes in 1990, the number of glacial lakes in the HKH region increased to 5974 (408.93 sq. km) in 2020 with an annual average increase of 13.63 sq. km (11.15%). A 2013 study characterized 36 lakes as potentially dangerous glacial lakes (PDGLs) that can pose GLOF hazards in the HKH region (Ashraf et al., 2021). This figure reached 47 in 2020 in the Koshi, Karnali, and Gandaki Basin alone (Bajracharya et al., 2020).

Around Karakoram, glaciers seem to be stable or gaining in mass in response to global climate change, a phenomenon known as 'The Karakoram Anomaly' (Dimri, 2021; Attaullah et al., 2022). Results show periodic surge cycles for the Khurdopin, Kyager, Shishper, and Chilinji glaciers of 15–20 years. The higher velocity of a glacier increases the risk of flooding downstream of the terminus because the transfer of a huge ice mass towards the terminus during the surge is a key factor for the formation of ice-dammed lakes, thus determining the magnitude and frequency of outburst flood events (Walder & Costa, 1996; Bazai et al., 2021). Shisphper Lake caused multiple damages to lives and infrastructures by draining twice in 2019, still bearing a risk given its GLOF susceptibility (Khan et al., 2021; Singh et al., 2023).

PDGLs in the Qinghai–Tibetan Plateau revealed integrated risk degree of county-based GLOFs by combining the hazard of PDGLs, regional exposure, vulnerability of exposed elements, and adaptability and using the analytic hierarchy process and weighted comprehensive method. All PDGLs area increased by 84.40% and was higher significantly than 4.06% of non-PDGLs (Wang et al., 2020).

The Central Himalayas have been experiencing the highest rates of mass loss, with temperatures driving mass loss in regions formerly sensitive to temperature and precipitation (Wang et al., 2013; Wang et al., 2020; Bhattacharya et al., 2021). While the Southern Himalayas are identified as a hotspot region for GLOFs, the average annual frequency of 1.3 GLOFs shows no discernible posterior trend despite reported expansions in glacial lake areas across much of the Hindu-Kush Karakoram Himalaya Nyainqentanglha (Gardelle et al., 2011; Nie et al., 2017).

Despite the conclusive evidence about spatiotemporal differences of climate change on glaciers and glacial landforms, there still lacks a sufficiently dense network of meteorological stations over high-altitude areas of HKH. Therefore, studies typically rely on reanalysis data and/or model-reconstructed products to investigate the features of extreme climate events (Hartmann and Buchanan, 2014; Palazzi et al., 2015; You et al., 2017).

2.3 Status of Glaciers and Glacial Landforms in Nepal

Consistent with the global and regional trends, Nepal faces continued elevation-dependent warming, such that mountain environments experience more rapid changes in temperature than environments at lower elevations (DHM, 2017; Thakuri et al., 2019). A high-quality daily temperature observation from 46 stations across the country spanning 1980–2016 reveals a widespread warming trend, with maximum temperatures increasing at approximately 0.04°C per year and minimum temperatures at about 0.02°C per year, particularly evident in the mountainous regions compared to valleys and lowlands (Karki et al., 2019). Consequently, there is evidence of rapid deglaciation, which has a national and regional scale impact on water resources (Shrestha & Aryal, 2011; Parajuli et al., 2015; Molden et al., 2022).

The earliest extensive field-based glaciological investigations took place in the 1980s in the AX010 glacier in the Everest region (Ageta, 1983), the Yala glacier in the Langtang region (Ono, 1985), and the Rikha Shamba glacier in the Mustang region (Higuchi, 1977). Their long-established database has given them the title of benchmark glaciers in the context of Nepal (Khadka et al., 2023).

A detailed analytical model and numerical ice flow model suggest a response time of 50 years for AX010 to climate change, anticipating an initial terminus response within approximately 8 years, consistent with the acceleration of glacier retreat rates observed historically (Christensen, 2007; Adhikari et al., 2011). Stumm et al (2021)'s work during 2011-2017 on average annual mass-balance rates measurement of Yala and Rikha Samba glaciers found a high negative value strongly in correspondence with Fujita et al in 1998, and Baral et al in 2017. Mapped Landsat images since the 1980s show an average estimated glacier ice reserve loss of 0.326 km3 near the hidden valley (Lama et al., 2015), whereas Kayastha (2017) further stresses the glacial mass loss in benchmark glaciers by showing a terminus retreat rates of 2.7 m. a^{-1} (1978-1989) to 16.7 m a^{-1} (1989-2004) for AX010, 3 to 4 m.a^{-1} between 1987 and 1996 for Yala, and 10 m.a^{-1} between 1974 and 1994 for Rikha Samba, respectively.

In the Khumbu region, glacial lakes have expanded significantly due to glacial shrinkage (; Bajracharya, 2010; Mool et al., 2011; Bajracharya et al., 2020; Peppa et al., 2020; Watson et al., 2020). Haritashya et al (2018), Maskey et al (2020), and Watson et al (2020) stress the increasing trend in the lake area of Lower Barun through Landsat and Corona satellite imagery, confirming the visible changes in a short geological timescale. Similar changes are observed in Imja, Chamlang, Lumding Tsho, Tsho Rolpa, and other unnamed lakes of concern (Lamsal et al., 2016; Thakuri et al., 2016; Khadka et al., 2019; Peppa et al., 2020). To neutralize the future consequences of GLOF, lake-lowering initiatives are in place at some glacial lakes but further measures are required to fully reduce the associated risks (Bajracharya et al., 2020; Peppa et al., 2020).

Glacier change in the Manaslu region appears to vary spatio-temporally, although studies agree on a sharp negative trend in geodetic mass balance after the 2000s (Robson et al., 2018; Racoviteanu et al., 2022). Debris-covered, and lake-terminating glaciers have experienced stronger melting rates when compared to clean-ice and land-terminating glaciers (Racoviteanu et al., 2022; Shrestha et al., 2020).

In the East, Ojha et al (2016) observed a loss of 11.2% ($0.7 \pm 0.1\%\ a^{-1}$) of debris-free glaciers. The number of glaciers reportedly increased by 5% due to fragmentation, while 61 glaciers covering an area of less than 2.4 sq. km have vanished since 1992 (Byers et al., 2020; Byers et al., 2024).

The study of glaciers and glacier landforms in the Himalayas, however, is notably limited compared to the European Alps and Iceland. Comprehensive research in the Himalayas gained momentum only after the inaugural Swiss Everest expedition in the early 1950s (Wyss-Dunant, 1953). This challenge is exemplified by the sparse deployment of unevenly distributed weather stations by the Department of Hydrology and Meteorology (DHM) in mountainous areas (DHM, 2024). Insufficient technical expertise and inadequate maintenance are further responsible for challenges in accurately recording meteorological data in the Nepalese Himalayas.

2.4 Glacial Melt Determination in High Mountain Areas

Studies on glacier melt and discharge rely on various modeling approaches to understand and predict meltwater contributions, particularly in complex terrains like high mountain regions. For instance, Hock (1998) utilized temperature index and energy balance models to simulate glacier melt with high temporal and spatial resolution on Storglaciaren in Sweden. The energy balance components such as net radiation, sensible heat flux, and latent heat flux were critical in determining melt rates, which were sensitive to aerodynamic roughness lengths and surface conditions. Similarly, Engelhardt et al (2014) employed gridded temperature and precipitation data to model mass balance and discharge in glacierized catchments in western Norway. In the broader context of the HKH region, Miller et al (2012) highlighted the variability in glacier melt contributions across east-west climatic zones, with significant implications for water resources in the Indus, Ganges, and Brahmaputra basins.

In Nepal, several studies have developed and applied hydrological models to estimate glacier melt contributions to river discharge through area-altitude distributions and water-energy exchange gradients. Pradhananga et al (2014) used a positive degree-day model (PDDM) to estimate current and future discharge from the Langtang River basin, calibrating the model with historical data and projecting future scenarios based on downscaled climate data. This model showed sensitivity to temperature variations and glacier area changes, predicting shifts in discharge patterns with ongoing climate change. Similarly, Racoviteanu et al (2013) used an elevation-dependent ice ablation model combined with remote sensing data to quantify glacier melt contributions in the Trishuli and Dudh Koshi basins. Parajuli et al (2015) further modified a temperature index model to estimate meltwater discharge from the debris-covered Lirung Glacier, achieving accurate results despite data limitations.

CHAPTER III: METHODOLOGY

3.1 Study Area

ICIMOD has classified PDGLs in the Koshi, Gandaki, and Karnali river basins spread across the Tibet Autonomous Region (TAR) of China, India, and Nepal (Bajracharya et al., 2020). Their classification is based on the characteristics of the lakes and dams, their physical environment, the properties of the source glaciers, and other factors such as seismic activity, human impact, and extreme climatic conditions that contribute to the instability of glacial lakes. Among the 47 total PDGLs identified, 25 are in the territory of the TAR, China, 21 are located in Nepal (Figure 3.1), and one PDGL is in India.

Our research investigates the 21 PDGLs of Nepal, as shown in (Table 3.1). Each lake is identified by a unique naming ID provided by ICIMOD, based on the Global Land Ice Measurement from Space (GLIMS) ID system established by Colorado's National Snow and Ice Data Center. These IDs are assigned because only a portion of the lakes have official names or generally recognized local designations. Furthermore, these IDs serve as essential identification since they include the longitude and latitude coordinates of each polygon's centroid. The GLIMS ID format consists of 15 characters (e.g., GLxxxxxxEyyyyyN), with 'GL' designating Glacier Lake, 'E' representing East, and 'N' denoting North; '5y' is a three-digit degree decimal latitude; and '6x' is a three-digit degree decimal longitude.

Table 3.1: 21 Potentially Dangerous Glacial Lakes of Nepal

SN	Glacier Lakes	Rank	Basin	Sub Basin	Elevation (m)
1	GL086612E27779N	I	Koshi	Dudh Koshi	4829
2	GL086858E27687N	I	Koshi	Dudh Koshi	4762
3	GL086957E27783N	I	Koshi	Dudh Koshi	5197
4	GL086977E27711N	I	Koshi	Dudh Koshi	4636
5	GL086925E27898N	I	Koshi	Dudh Koshi	5002
6	GL086935E27838N	I	Koshi	Dudh Koshi	5201
7	GL086928E27850N	I	Koshi	Dudh Koshi	5394
8	GL086917E27832N	I	Koshi	Dudh Koshi	5359
9	GL086476E27861N	I	Koshi	Tama Koshi	4550
10	GL087596E27705N	I	Koshi	Arun	4772
11	GL087092E27798N	I	Koshi	Arun	4530
12	GL087749E27816N	I	Koshi	Tamor	4902
13	GL087945E27781N	I	Koshi	Tamor	4862
14	GL084485E28488N	I	Gandaki	Marsyangdi	4033
15	GL085630E28162N	I	Gandaki	Trishuli	4983
16	GL086958E27755N	II	Koshi	Dudh Koshi	4936
17	GL087095E27829N	II	Koshi	Arun	5208

18	GL082673E29802N	II	Karnali	Mugu	4703
19	GL087934E27790N	III	Koshi	Tamor	4934
20	GL087893E27694N	III	Koshi	Tamor	4571
21	GL087632E27729N	III	Koshi	Arun	4938

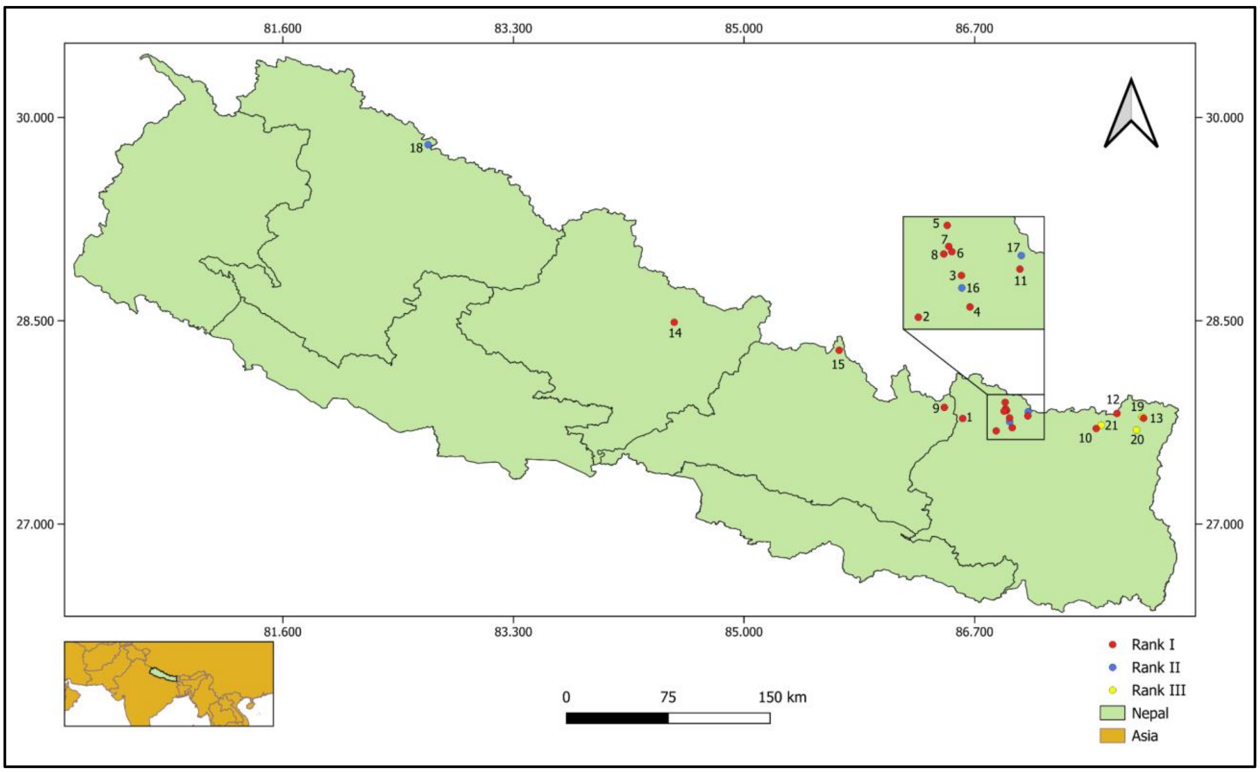


Figure 3.1: 21 Potentially Dangerous Glacial Lakes (PDGLs) of Nepal

GL084485E28488N, locally referred to as Dona Tal is located just south of the Tibetan Plateau in Western Nepal, flowing as Dona Khola in the Marsyangdi River basin, and ending in the Kali Gandaki River Basin (Figure 3.2). It began as a series of supra-glacial ponds that coalesced about 50 years ago to form a moraine-dammed lake (Mool et al., 2011). It is a ranked I PDGL sitting at an altitude of 4050 m a.s.l and exceeding the storage capacity of $35x10^6$ m^3 at 28°29.24′N latitude and 84°29.17′E longitude. The lake is fed by the heavily debris-covered Thulagi Glacier, which is a temperate glacier residing adjacent to the flanks of Mount Manaslu (8156 m a.s.l.). The Glacier has an annual geodetic mass balance of -0.21 ± 0.38 (m.w.e. a-1), and a glacier retreat rate of 30 $m.a^{-1}$ from 1991 to 2016 (Pelto, 2016; Brun et al., 2017). Along the glacier centreline, the Dona Lake expanded by 203m within 20 years (2008-2018) (Haritashya et al., 2018).

It is categorized as a moderately hazardous glacial lake with the threat it poses to settlements downstream and their associated socioeconomic activities in the event of a GLOF (Rounce et al., 2016). Around 16000 domestic and international tourists visit the Dharapani area in the Marsyangdi basin annually. The local people are involved in tourism, trade, and wage-based livelihood options, and the river basin is home to three major hydroelectricity projects - The Upper Marsyangdi Hydropower project in Bhulbule, Middle Marsyangdi in Lamjung, and Lower Marsyangdi in Abukhaireni (Khanal et al., 2015; Maskey et al., 2020).

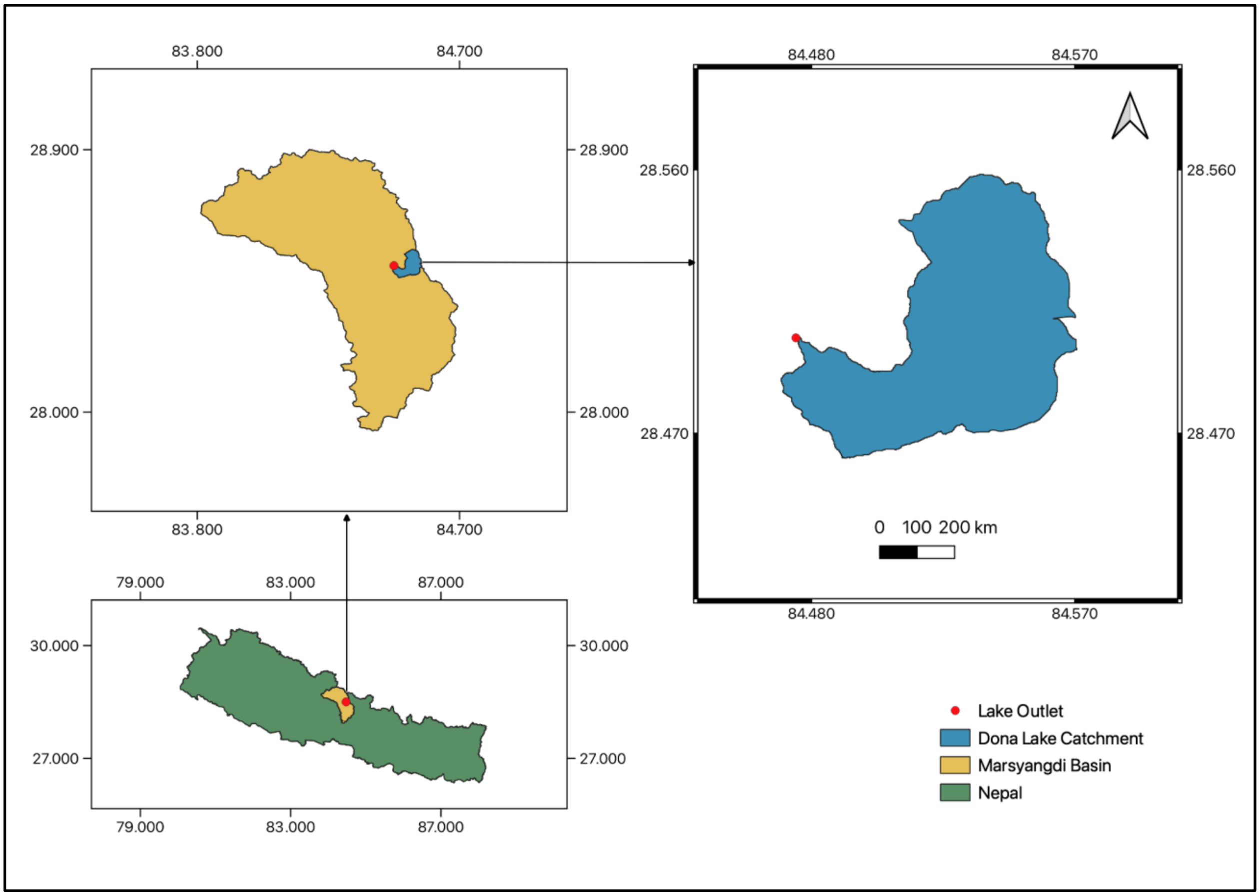


Figure 3.2: Dona Lake Catchment Area

3.2 Research Design

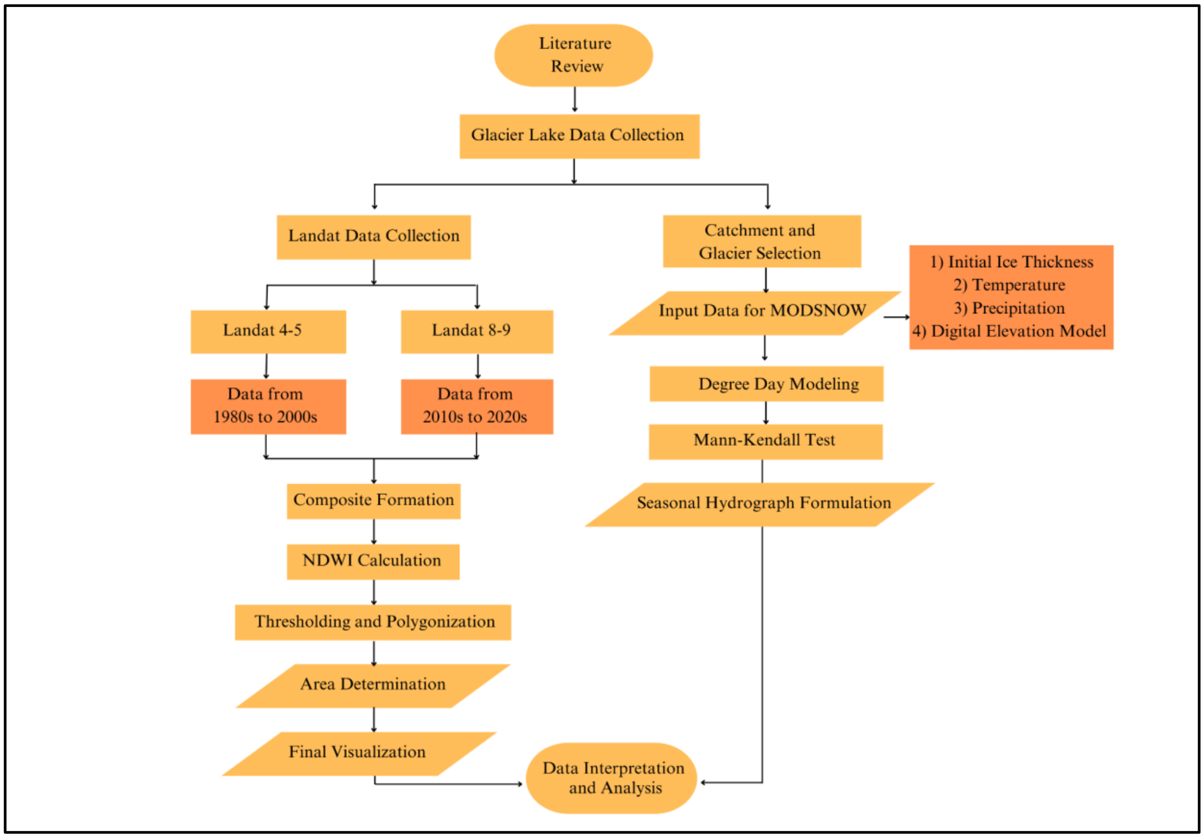


Figure 3.3: Flow chart of research design for Glacier Lake area and inflow analysis

(Figure 3.3) describes the sequential steps used to gather, process, and analyze data on area determination of glacier lakes and glacial melt contributions. The methodology combines satellite data gathering, image processing tools, and modeling approaches to determine the extent of PDGLs, as well as the input of glacial meltwater into Dona Lake in a clear and methodical approach to meeting our study objectives.

3.3 Data Collection and Analysis

3.3.1 Glacial Lake Area Determination and Visualization

3.3.1.1 Data Source and Collection

To track the decadal variations of the PDGLs, multi-temporal Landsat imagery from two satellite sensors was used: the Thematic Mapper (TM) of Landsat 4-5, and the Operational Land Imager (OLI), and Thermal Infrared Sensor (TIRS) of Landsat 8-9. These satellites have continuously acquired images of the Earth's land surface in high spatial resolution and extent since the 1970s (USGS, 2015). Given their free accessibility, data sources like United States Geological Survey (USGS) Earth Explorer and Sentinel Hub were utilized to obtain geographical data from the 1980s to the 2020s. In particular, data for the 1980s, 1990s, and 2000s were obtained using Landsat data 4-5, and for the 2010s and 2020s using Landsat data 8–9. Bearing in mind the cloud coverage, seasonal and inter-annual snow conditions, and data gaps, only the most appropriate images were chosen for the study to minimize potential errors in the outcome.

3.3.1.2 Composite and NDWI Calculation

Following data collection, several raster layers were combined into a single virtual raster, called Catalog, to generate a composite image using Google Earth Engine. This approach streamlined data management by combining existing raster datasets into a consistent catalog format, increasing accessibility and simplicity of use.
After completion, the Normalized Difference Water Index (NDWI) was applied to detect water bodies from the acquired data. It is a remote sensing-based indicator developed by McFeeters (1996) to enhance the water-related features of the landscapes by using green and near-infrared bands to highlight water bodies (Szabo et al., 2016).

The formula to calculate NDWI is:

NDWI = (Green - NIR) / (Green + NIR)

The formula was modified in the context of different Landsat images based on the image bands and the color they represent.

Landsat 1-5 MSS NDWI = (B01 - B04) / (B01 + B04)

Landsat 4-5 TM NDWI = (B03 - B05) / (B03 + B05)

Landsat 8-9 NDWI = (B03 - B05) / (B03 + B05)

It is generally considered that water bodies are represented by index values larger than 0.5. Built-up areas often correlate to values between 0 and 0.2, whereas vegetation typically corresponds to much smaller values (Sinergise., n.d.).

3.3.1.3 Thresholding

Thresholding, a segmentation technique, was used to produce a binary image by dividing a grayscale image, an NDWI map, into two regions based on a predetermined threshold value. In a binary image, each pixel was assigned one of two values – 0 or 1, which represent distinct features or classes, making image analysis simpler. The specific threshold value was established to distinguish between water and land surface. The process was carried out by applying a conditional statement. Each pixel in the NDWI raster dataset was compared to the given threshold value. If a pixel's NDWI value exceeded the threshold value (say, 0.2), it was categorized as water (given a value of 1); otherwise, it was classified as land (given a value of 0). A threshold value range of (0.01 - 0.3) had to be applied in our case. This step was repeated for each pixel in the raster dataset to generate binary images for polygonization.

3.3.1.4 Polygonization and Boundary Delineation

Using the polygonization technique, raster data was then converted into vector data by creating polygons for all connected regions of pixels in the raster sharing a common pixel value. Each polygon was created with an attribute indicating the pixel value of that polygon. Since a vector representation is convenient for data entry and editing, we then refined the lake boundary for an accurate representation of our data.

3.3.1.5 Area Determination and Visualization

Following vectorization, QGIS was used to calculate the lake area through a robust toolkit for attribute management and spatial analysis, the Field Calculator. Within the Field Calculator interface, a specific expression, 'area($geometry)' was employed to calculate the area of the Glacier Lake polygon. QGIS then calculated the area contained by the polygon geometry in square meters. This formula uses the vectorized lake polygon's inherent spatial features to provide an accurate estimation of its extent (Mapscaling, 2023).

Subsequently, the evolution of the lake's bounds was visually traced by overlaying delineated maps generated after vectorization. A recent sentinel image was used as base imagery to validate the lake boundary. By superimposing these boundary maps, the changes and evolution in the lake's extent throughout time were tracked.

3.3.2 Glacial Melt Trend Analysis of the Dona Lake

3.3.2.1 Model Specifications

The MODSNOW tool was used to estimate daily glacial melt amounts from 2000 to now. This operational software package facilitates real-time monitoring of the cryosphere and water resources by processing raw Moderate Resolution Imaging Spectroradiometer (MODIS) data and employing advanced algorithms to eliminate cloud cover. The output is a ready-to-use, cloud-free snow cover map and a daily report featuring spatiotemporal snow statistics for predefined river basins. The MODSNOW tool operates in both operational and non-operational modes. In the operational mode, it is set up as a scheduled task on a local computer, enabling automatic execution without user interaction and delivering daily snow cover maps. In the non-operational mode, it can process historical time series of snow cover maps from MODIS. Designed to work with the MODIS snow cover product, MODSNOW utilizes data from MODIS, an optical sensor on the Terra and Aqua satellites, which have been conducting Earth observations since March 2000 and July 2002 respectively (Gafurov et al., 2016).

The MODSNOW tool employs the degree day model approach to calculate discharge, which, despite its simplicity, is deemed extremely effective (Zhang, 2006). The model is based on the relationship between ice melt and air temperature (Braithwaite, 1995; Liu et al., 1998; Hock, 2003).

3.3.2.2 Input Data Source and Collection

Farinotti et al (2019) was used to obtain the initial glacier ice thickness.
The daily precipitation and temperature data was sourced by MODSNOW, from the ERA5 dataset to run the degree day model. Before executing the process, MODSNOW performed bias correction on the temperature data using data from a nearby meteorological station in Dharapani and interpolated the rainfall data to a finer spatial resolution of 25m.

3.3.2.3 Working of the Glacial Module

An outlet was defined at the lake’s end to determine the inflow contribution to Dona Lake and encompass all the glacier melt from the lake’s surroundings. Then, the Digital Elevation Model (DEM) was run by the MODSNOW tool to compute the catchment area contributing to the lake. Subsequently, the debris-covered Thulagi glacier, residing adjacent to the flanks of Mount Manaslu was identified as the contributor for further analysis. The study area was then converted into individual grid cells and later aggregated to generate the daily glacial melt data.

The following relation was used to obtain the melt:

$$\text{Glacier Thickness}_{t} = \text{Glacier thickness}_{t-1} + \text{Accumulation}_{t-1} - \text{Ablation}_{t-1}$$

Where,

$\text{Accumulation} = \text{Snow Depth}_{t} + \text{basal turnover coefficient}$

$\text{Ablation} = $ if $Ta > To$ [$\text{Ablation}_{t} = ddf_{ice} * (Ta - To)$]

if $Ta < To$ [$\text{Ablation}_{t} = 0$]

Where,

Ta is the daily mean temperature and *ddf* is the degree day factor.

The fixed parameters of the glacier melt module;

Basal turnover coefficient = 0.00065 m.w.e.

Degree day factor of ice = $ddf_{snow} * 1/0.7$ ($ddf_{snow} = 0.005$)

Threshold temperature (To) = ~ 0°C

Discharge (Q) = Actual ice melt * cell area / month * 86400

3.3.2.4 Trend Analysis

Before conducting trend analysis, the daily glacial melt data from MODSNOW was aggregated into monthly averages to smooth out short-term fluctuations and highlight long-term trends.

The Mann-Kendall test was used to determine the presence of a monotonic trend in the time series data. This non-parametric test can detect trends in environmental data over time, even when the data does not have a normal distribution (Hirsch et al., 1982). The significance level (α) was set at 0.05 (at 95% Confidence Level) and the test was performed in RStudio using the Kendall package developed by A.I. McLeod with the following command: install.packages ("Kendall") (Hipel et al., 1994).

Sen's slope estimator was used to quantify the Mann-Kendall test-identified trend. This method yields a reliable measure of the rate of change in the variable of interest over time, calculated as the median of all possible pairwise slopes (Sen, 1968).

To facilitate the interpretation of seasonal and annual trends in glacial melt, RStudio was used to create a series of visual representations of the data such as (1) An Inflow contribution hydrograph to demonstrate the daily and seasonal meltwater contribution to Dona Lake. (2) A summary hydrograph with standard deviation to show the overall trend in glacial melt over the study period. (3) Average seasonal temperature and precipitation graphs to investigate the relationship between climate variables and trends in glacial melt. These visual tools provide a clear and comprehensive view of the melt dynamics during the study period.

3.3.2.5 Consideration of Temporal Dynamics and Losses

Since the catchment area contributing to Dona Lake is comparably small, the temporal delays in meltwater inputs are deemed negligible. Therefore, all the meltwater generated on a given day is expected to enter the lake that day. Losses like infiltration and evaporation are not accounted for since the impact is negligible due to the high elevation and low surface temperature.

CHAPTER IV: RESULTS AND DISCUSSION

4.1 Decadal Trends in the Area of PDGLS

The Landsat images since the 1980s reveal an overall increasing trend in the area of 14 of the 21 Glacial lakes and a decreasing trend in the remaining PDGLs. Out of the 14, 4 have experienced a change more than double their initial size, 2 of them have seen a significant change, while the rest of the 7 have moderate to low changes during the last four decades. Among the 7 with a decreased area, the highest reduction in size is 22%. Some lakes display a steady pattern of increasing or decreasing area, while others show irregular changes that may be attributed to seasonal variations, irregular data collection intervals, human error, or local environmental changes.

4.1.1 Substantial variations

Lower Barun, Imja, Lumding Tsho, Chamlang South, Dona Taal, and Tsho Rolpa have experienced large changes in the area over the study period. Lower Barun has the highest gradient among the PDGLs, increasing almost five times over the last 40 years, overtaking Tsho Rolpa as one of the largest glacial lakes in Nepal. It has enlarged from 0.48 sq. km to 2.34 sq. km with an average increase per decade of 0.4641 sq. km. Imja follows Lower Barun with the second most variation in its area. A 0.601 sq. km in 1989 expanded to 1.713 sq. km in 2023. Lumding Tsho (GL086612E27779N) ranks third with an overall 138% change since its 1988 extent. Chamlang South, Dona Lake, and Tsho Rolpa have increased at a rate of 0.0864, 0.0807, and 0.046 sq. km decadally. Substantial increases in overall percentage in the area of lakes with GLIMS ID GL086977E27711N, GL082673E29802N, and GL087596E27705N are noticeable as well. Conversely, in Lake GL087945E27781N, we observe a substantial reduction of 22.31% in the Lake area when compared to its initial domain.

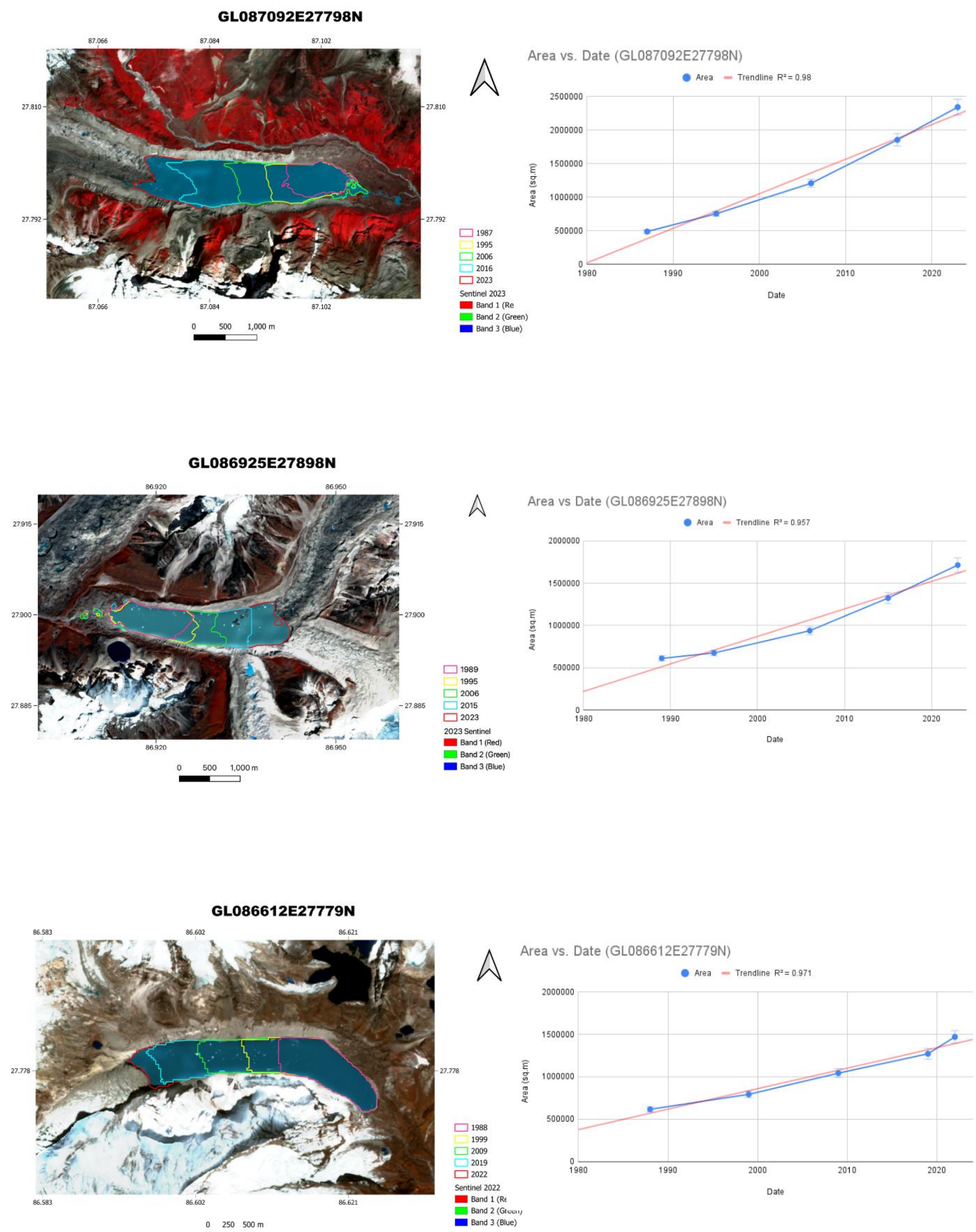


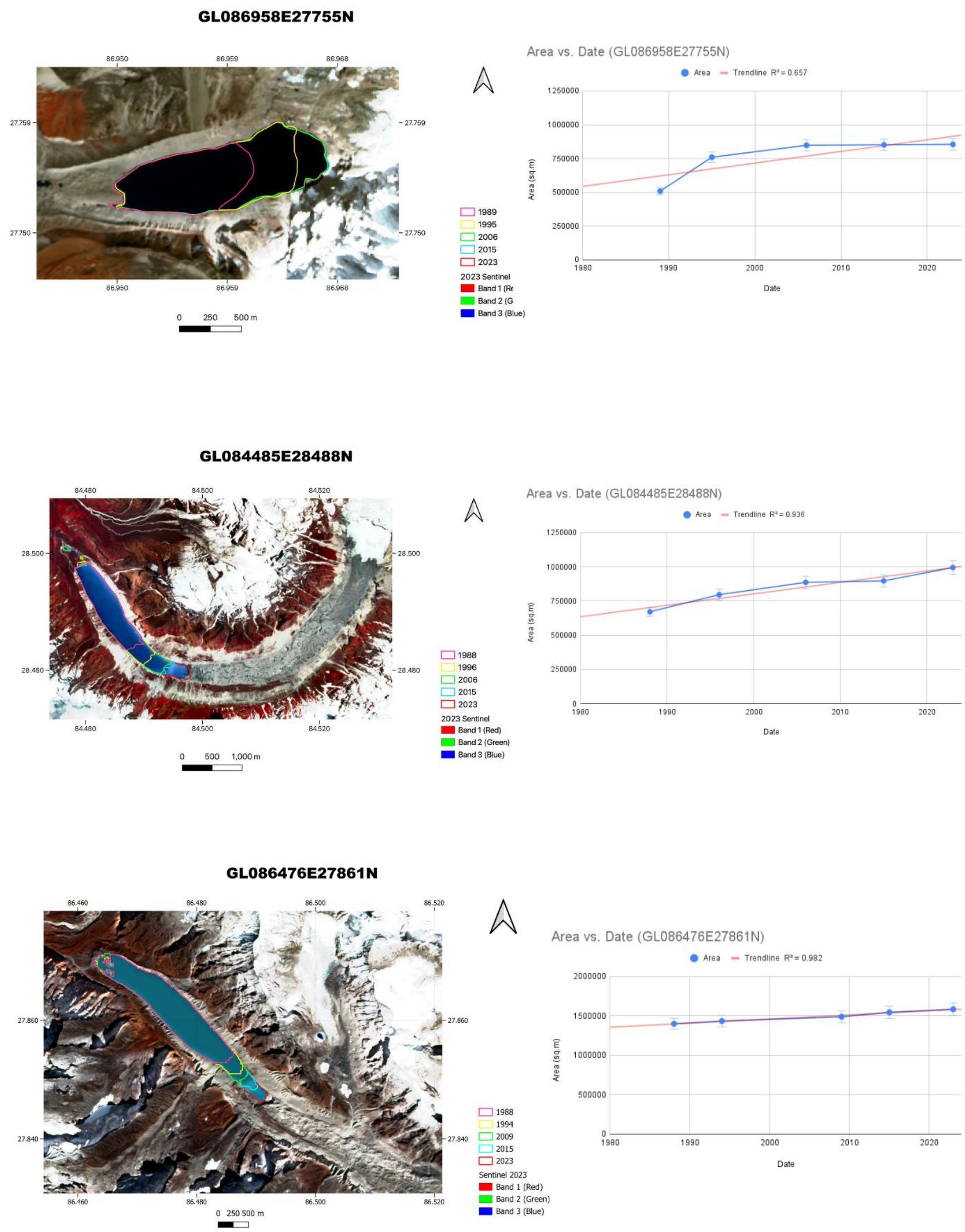
Figure 4.1: Area Visualization of Lower Barun, Imja, and Lumding Tsho, with a chart view including a 5% error bar

Evidence suggests Lower Barun (GL087092E27798N) grew more rapidly after the 2000s (Figure 4.1). Our study demonstrates an increase of 51% in its area since then. This data corresponds with both second and third-order polynomial projections made by Haritashya et al. (2018), who relate this rapid expansion to large glacial calving from partial buoyancy of the source glacier, and high glacial velocity near the terminus due to proximity to icefall. Bajracharya et al (2020) argue about the vulnerability of the lake to landslides and avalanches from the right wall of the lake. The Upper Barun Lake and two other smaller lakes in the catchment above further pose a danger of lateral dam failure in case of a cascading event. A two-dimensional dam break model and inundation propagation indicate damages to properties as far as 85 km downstream if both the Baruns were to suffer an outburst (Gouli et al., 2023). The terrain model in Google Earth Pro, on the other hand, points toward a stagnant Lower Barun after the glacier melts beyond the ridgeline.

Imja Lake is enlarging east and northeast towards its glacier sources, namely, Imja and Lhotse Shar glacier. Our obtained results for Imja Lake are linear with findings from Watanabe et al (2009) and Thakuri et al (2016) which show a slow to moderate increase till the 1990s, and renewed accelerated expansion after the 2000s. The renewed expansion has exceeded expectations, as the lake has increased more than the projected rate by Haritashya et al (2018). Most of the inflow contribution is from Lhotse Shar, as findings highlight a 45-50 $m.a^{-1}$ higher surge in comparison to Imja due to higher surface irradiance. The presence of small supraglacial lakes in Lhotse Shar stipulates lake expansion to a greater extent as the glacier retreats. Amphu Lapcha glacier in the southern lateral end has developed a few supraglacial ponds of its own that could empty itself into Imja Lake and set off a potential trigger after further retreat.

Imja is classified as having a moderate hazard and risk from a GLOF event, partly due to the lake-lowering effort by DHM in the downstream community of Dingboche (Budhathoki et al., 2010; Rounce et al., 2016).

Shrestha and Balla (2011) found Lumding Tsho's extent to be 0.104 sq. km in 1963. Our study finds a 0.6 sq. km area in 1988, 0.7 sq. km in 1999, and 1.2 sq. km in 2019, aligning with values Khadka et al (2019) determined in similar periods. By 2022, its area has risen to 1.4 sq. km. Lumding Tsho is expanding west toward its source glacier, which was retreating at a rate of 74 ma–1 from 2000 to 2007 (Bajracharya & Mool, 2009). Findings from Joshi & Bhattarai (2021) solidify the large contribution of the retreating Lumding glacier in the expansion of the lake after they detected a 0.00219 sq. km /year decrease in the snowline of the glacier source. Besides the area expansion, the surrounding topography of the lake enhances the associated risk from GLOF as cirque lakes and hanging glaciers with slopes ranging from 20° to > 50° pose a risk from a calving event and subsequent splash erosion in the glacial lake. Consequently, Rounce et al (2016) rated Lumding Tsho as a high-risk lake susceptible to both dynamic and self-destructive failure given the supporting evidence and the inadequate study conducted on the site, unlike lakes like Imja and Lower Brun (Khadka et al., 2019; O’Neill, 2021).



.

Figure 4.2: Area Visualization of Chamlang, Dona Lake, and Tsho Rolpa glacial lakes with a chart view including a 5% error bar

Chamlang South evolved from a series of supra-glacial ponds similar to other PDGLs, bearing a total area of 0.040 sq. km in the 1960s. It increased to 0.84 sq. km by 2006, which is a value that can be backed by Lamsal et al (2013). Since then, the lake area has remained relatively constant, maintaining a solid 0.85 sq. km in the 2010s and 2023. It is a rank II PDGL fed by a hanging glacier at its eastern side. The sloppy positioning of the source glacier poses a threat from ice avalanches, and the acclaimed seepage into the terminal moraine dam of the lake points towards a potential trigger of a flooding event (Lamsal et al., 2016). The voluminous lake could inundate several buildings, agricultural lands, and bridges downstream in such an event although the 500m long dead ice area between the lake and the end moraine is expected to neutralize the displacement waves produced in the event of snow/ice avalanche or rock fall into the lake, lessening the threat from a potential GLOF (Lamsal et al., 2013; Rounce et al., 2016). Small ponds can be seen in the dam that could virtually increase the lake area in the future, but further study is warranted in Chamlang to ascertain this finding in different scenarios for a potential burst projection (Khadka et al., 2019).

Compared to Imja and Lower Barun, the area change for Dona Lake (GL084485E28488N) is not considered as drastic despite residing at a lower elevation and having experienced a discernible increase (Figure 4.2). Haritashya et al (2018) link this behavior to low solar irradiance in the glacial terminus, lack of glacial surface processes, and narrow ice/water contact areas. The values from our research correlate with studies carried out in the past, but an error of ± 0.05 sq. km is detectable (Haritashya et al., 2018; Maskey et al., 2020). We have come across similar developments till the mid-2010s i.e. a linear trend till the mid-2000s, and a limited change in the next decade, but anomalous behavior in the size of the lake in recent years underline far higher development in area than projected from second, and third-order polynomials in 2023. This change comes simultaneously with the retreat of the heavily debris-covered Thulagi glacier through erratic changes in meteorological factors and the influence of external events like glacial calving (Pant & Reynolds, 2000; Maskey et al., 2020; Watson et al., 2020). (Annex D) conforms to this by showing an increasing trend of glacial melt inflow to the Dona Lake since 2000. Furthermore, the possibility of glacial calving from the source glacier, and mass movements from the lateral walls of the lake pose a threat of lake expansion and a possible burst trigger (Bajracharya et al., 2020).

Results for Tsho Rolpa Glacier Lake (GL086476E27861N) vary by ± 0.03 sq. km in regard to Peppa et al (2020). It was the largest PDGL when identified back in 2001. Currently, it ranks third highest in terms of area after the rapid expansion of Lower Barun and Imja after the turn of the century. Similar to Dona Taal, the narrow point of contact between glacial ice and water surface could have led to obtuse development, but further research is warranted to understand the effect of debris cover, sky view factor, and the involved glacial processes. The lowered water level in 2000 was never considered sufficient to fully eliminate the risks associated with a flooding event (Rana et al., 2000; Sherry & Curtis, 2017), hence the retreat of the calving, steep-moraine Trakarding glacier, and the hanging lake in a tributary glacier just above the lake domain need special consideration as horizontal expansion continues. The lateral moraine is attenuated; therefore, it threatens a possible trigger to the lake outburst and consequent impact on hydropower projects in the glacial-fed river system. It is classified as a high-hazard lake by Rounce et al (2016) given the highest number of casualties involved in case of a flooding event, similar to Dona Taal (Shrestha & Nakagawa, 2013; Chen et al., 2022).

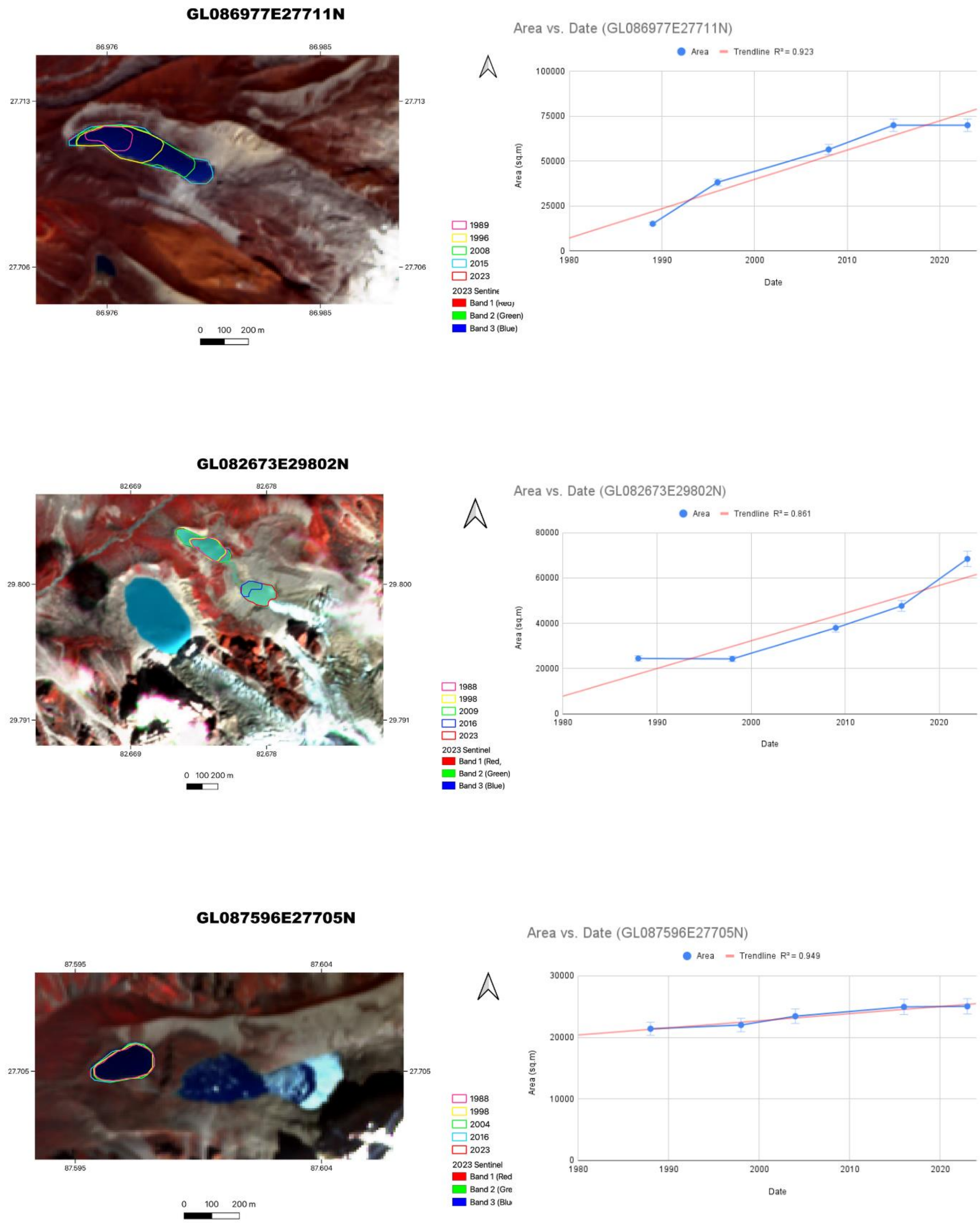


Figure 4.3: Area Visualization of lakes GL086977E27711N, GL082673E29802N and GL087596E27705N with a chart view including a 5% error bar

Lake GL086977E27711N has increased by more than three times over the study period; from 0.015 sq. km in 1989 to 0.069 sq. km in 2023. It is developing towards the calving source glacier that has been retreating throughout the years. Our findings highlight a linear increase in the lake area till 2015, and a virtually stable character since then. While it does not pose an immediate threat due to its distant proximity to communities downstream, the lake is still to be monitored closely as it lies in the same river basin as Chamlang Cho (GL086958E27755N), Hongu 2 (GL086957E27783N) and other clustered Glacial lakes of concern that could cause a catastrophic flooding event if combined.

Lake GL082673E29802N on the foothills of the Tibetian plateau in Mugu district has experienced a 31.21% average change in its area per decade. Despite ranking II, it has enlarged more than other ranked I PDGLs partly because of a depression filling overhanging the initial lake body (Figure 4.3). This has renewed the lake expansion after the 2010s, and is expected to continue growing given the hanging source glacier includes several crevasses. In case of a tensile failure, calving events followed by subsequent splash erosion can instigate a flood trigger although the overhanging boulder can still be relied upon as it protects the erosion of the dam. Another larger lake is being fed by the same parent glacier just below GL082673E29802N. As the glacier retreats, this shallow lake could overtop its dam and pose a threat from a GLOF as well.

A steady increase in the area of lake GL087596E27705N is distinguished (Figure 4.3). Although its size is diminutive compared to other lakes, it is ranked I since it lies under the constant threat of a cascading lake that might overflow to set off a GLOF. This cascading lake feeds GL087596E27705N and is in contact with the source glacier at its terminus. When observed through Landsat images over the study period, it seems to be growing exponentially. As the dam width of the PDGL is small, a possible displacement wave could trigger a collapse and release a hefty volume of discharge through the river channel downstream.

In terms of area reduction, lake GL087945E27781N is the only lake with substantial variation above 20% (Annex B). Despite the decrease in area, the lake ranks I under the PDGL category due to the threat it presents from its geomorphological and hydrological characteristics. The relatively short length of the dam (<400 meters) and the narrow crest width (<20 meters) suggest limited structural integrity, which is compromised by the steep side slopes prone to landslides (Bajracahrya et al., 2020). This classification highlights the dynamic and potentially catastrophic processes that can be triggered by the existing environmental conditions.

4.1.2 Moderate variations

Among the 11 lakes exhibiting moderate fluctuations, 5 are gradually expanding, while the areas of 6 lakes are declining when compared to their 1980s extent.

All the Rank III lakes i.e. GL087934E27790N, GL087893E27694N, and GL087632E27729N observed a very minimal rate of change over the decades. Two of these lakes exhibited the least fluctuation among all PDGLs remaining almost stagnant. Meanwhile, Nupchu Pokhari (GL087934E27790N) displays a slow but gradual expansion (Table 4.1). A cluster of Rank I lakes – GL086935E27838N (Hongu1), GL086928E27850N, and GL086917E27832N – appear to have shrunk by 5.35%, 1.38%, 10.64% whereas, Lakes GL086957E27783N (Hongu 2) and GL085630E28162N have demonstrated incremental growth of around 7.32% and 5.59% respectively. Among the Rank II lakes, Hanging Lake GL087095E27829N distinguishes itself by displaying a restrained expansion rate of just 0.62 % per decade. Lake GL087749E27816N has reduced by approximately 7.8% and Lake GL086858E27687N by 5.3% during the study period.

Table 4.1: Decadal area changes of lakes with moderate variations from the 1980s-2020s and their Average rate of change per decade

Lake	Area (sq.km.)					Average rate of change per decade (sq.km.)	The average rate of change per decade (%)
	1980s	1990s	2000s	2010s	2020s		
GL087934E27790N	0.114078	0.114572	0.115507	0.116292	0.116882	0.0007	0.6
GL087893E27694N	0.026116	0.032848	0.032844	0.026438	0.026053	~0	1.2
GL087632E27729N	0.03117	0.030329	0.031681	0.032011	0.030836	~0	-0.21
GL086935E27838N	0.304944	0.288409	0.284249	0.289301	0.288604	-0.004	-1.33
GL086928E27850N	0.45906	0.442989	0.438727	0.452648	0.452688	-0.0015	-0.32
GL086917E27832N	0.346587	0.360378	0.336559	0.321637	0.309694	-0.0092	-2.69
GL086957E27783N	0.735871	0.784957	0.786639	0.789113	0.78978	0.0134	1.82
GL087095E27829N	0.109268	0.110572	0.110385	0.111231	0.112007	0.0006	0.62
GL086858E27687N	0.288546	0.295762	0.300686	0.283953	0.304066	0.0038	1.42
GL087749E27816N	0.180291	0.175652	0.163506	0.167725	0.166216	-0.0035	-1.95
GL085630E28162N	0.055884	0.057395	0.056821	0.058263	0.059008	0.0007	1.38

According to Bajracharya et al (2020), the dams of Lake GL087632E27729N and Lake GL086858E27687N are positioned at a high gradient, potentially amplifying the consequences in case of an outburst trigger. As for Lake GL087893E27694N, its area is attributed to the shrinking of the lake extension at its eastern side. This reduction can establish a low-risk front, but its topographical characteristics – a steep slope and a short dam length – highlight the lake's vulnerability to a flooding event.

Despite a minimal change experienced by Nupchu Pokhari, this character could be considered alarming since there have been recorded instances of minor flooding in the area, raising concerns about the lake being involved as a potential source. Additionally, the trend analysis of GLOF events in the Tamor basin since 1963 further corroborates the suspicion (Byers et al., 2024).

Notable morphological changes are observed in Hongu1 (GL086935E27838N) where sediment deposition from the retreating source glacier has led to gradual landmass formation, reducing the lake’s area by 5.35%. This finding contrasts with Bajracharya et al (2020) who imply an extension adjacent to the glacier's snout. On its southern end, a ponded water body has slowly tendered towards the lake, fairly bumping the area by a small margin in the 2010s. Despite appearing relatively stable, the presence of hanging lakes on both sides of Hongu1 poses a potential risk of triggering cascading events. One of those hanging lakes is Lake GL086928E27850N, which, similar to Hongu1, tends to coalesce with a neighboring pond over time, ensuing a trajectory of further expansion. It lies under constant threat of landslides, avalanches, and cascading lakes that could nosedive from upstream. The stability of its dam should therefore be monitored to prevent a potential GLOF event. Lake GL086917E27832N on the other hand, is unlikely to experience cascading events due to its terrain structure despite its proximity to the two neighboring lakes. Its dam length, however, raises concerns regarding stability and containment, potentially increasing its vulnerability to outburst events.
Moreover, the lake, similar to GL086917E27832N, appears to be shrinking in size due to probable sediment deposition, a common occurrence near the source glacier.

Lakes such as GL086957E27783N (Hongu 2) and GL085630E28162N lakes share identical characteristics, like having a parent hanging glacier and a short dam length, making them highly vulnerable to outbursts in the case of triggers. In the case of Lake GL086858E27687N, there are chances of landslides and ice avalanches from the headwater (Bajracharya et al., 2020), potentially threatening the nearby small village of Khote to its outbursts.

4.2 Trend of glacial melt in Dona Lake

4.2.1 Statistical Variations

Through statistical analysis of observed glacial melt from Dona Lake using the MODSNOW tool, we observe an overall increasing trend in inflow contribution from glacial melt since 2000 (Annex D). Three peak glacial melt discharge rates (above 1 m3/sec) were observed in the first decade, whereas observed discharge peaks can be seen since then. The record highest was observed in 2017 (1.22 m3/sec).

Distinct monthly and seasonal patterns are visible, with February (Winter) contributing the lowest melt (0.00067 m^3/sec) and September (Monsoon) the highest (0.6277 m^3/sec) (Annex H). Parallelly, February and October encounter the lowest (0.006 m^3/sec) and highest (0.319 m^3/sec) standard deviations across all months (Figure 4.4).

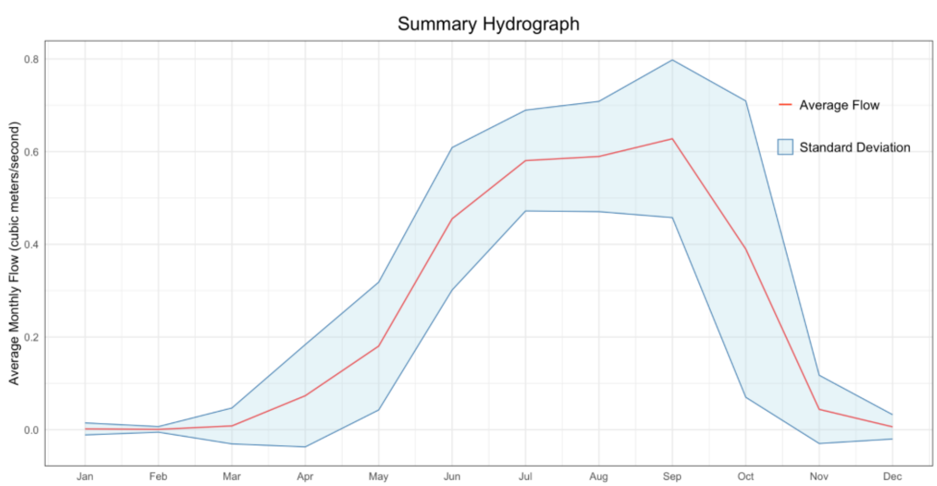


Figure 4.4: Summary Hydrograph

(Table 4.2) shows the results obtained from the Mann-Kendall test:

Table 4.2: Seasonal Trend of Glacial Melt from Thulagi Glacier

Test_Series	**P_value**	**Z_statistic**	**Sense_slope**	**varS**	**tau**	**Alt_hypothesis**
Winter	0.832	-0.211	-0.0017	1816.67	-0.033	TRUE
Pre-monsoon	0.901	-0.124	-26.107	1625.33	-0.021	TRUE
Monsoon	0.157	1.413	84.22	1625.33	0.210	TRUE
Post-monsoon	0.413	0.818	172.07	1625.33	0.123	TRUE

The Mann-Kendall test and Sen's slope suggest that the alternative hypothesis is true for all seasons, but evidently, all trends are not statistically significant (Table 4.2). This means there is a weak trend of seasonal glacial melt over the study period. Pre-monsoon and Winter seasons exhibit a weak decreasing trend, whereas monsoon and post-monsoon trends appear weak and increasing. Likewise, every pair of observations from winter to pre-monsoon is discordant, and the latter is potentially concordant. Notably, the early months for Pre- and Post-monsoon have P-values approaching a significance level of **α** = 0.05, indicating a closely statistically significant behavior.

As glaciers in Nepal are summer accumulation type, they have a non-maximum type of balance rate. Maximum accumulation and ablation occur in the same season. It is therefore difficult to directly observe changes in glacial melt but accumulation can be estimated based on the relationship between temperature and solid precipitation patterns (Ageta, 2018). Shrestha et al (2020) determined glacial ablation and melt rates using conductive heat flux and energy balance methods on the nearby Ponkar Glacier. Using an Automatic

Weather Station (AWS) to monitor meteorological parameters on-site, they observed the highest ablation and melt rates during the monsoon, followed by the pre-monsoon and post-monsoon seasons. Our findings confirm the melt rates observed in the monsoon and winter seasons but vary from patterns of rates in post and pre-monsoon where we see a linear observation while taking into account temperature gradients and consequent glacial melt. The differing melt rates between Ponkar and Thulagi glaciers can be attributed to the classification of the source glacier (Lake terminating/ Land terminating), variations in debris cover on the glacier surfaces, and differences in precipitation of the glacier catchment (Juen et al., 2014; Brun et al., 2019; Racoviteanu et al., 2021). The rugged topography of the Himalayas further causes local and regional variations in rainfall. Minor changes in data sources affect the interdependence of catchment rainfall and subsequent glacial melt (Owen and Benn, 2005). Our results are more closely linked with Awasthi & Owen (2020) who discovered a statistically significant pattern of increasing temperature, and an insignificant pattern of decreasing precipitation when examining metrological indices from around Nepal: inflow patterns are consistent concerning temperature trends but show perplexed relation with precipitation.

4.2.2 Climatic Influences

The temperature trend of Dharapani, Manang, strongly correlates with variations in melt patterns but the precipitation trend of the larger Marsyangdi Basin somewhat contrasts the observed results (Annex E, Annex F). During the pre-monsoon period, average precipitation and temperature rates rise above their post-monsoon counterpart, but the glacial melt is ultimately higher in the post-monsoon season. Minimal temperature gradients throughout these periods result in notable fluctuations in inflow levels. In monsoon and winter, close correlations emerge between temperature and rainfall trends with inflow dynamics: increased temperature and rainfall coincide with the heightened inflow of glacial melt, and vice versa. During winter, however, cold temperatures freeze the lake surface below 0°C and maintain a nominal glacial melt, which is considered base flow values (Racoviteanu et al., 2013).

Changes in temperature and precipitation patterns over individual years explain the crest and trough in the chart (Figure 4.5) over similar periods, suggesting interannual variations. The years 2004 and 2010 for example, witnessed a spike in pre-monsoonal inflow linear with higher temperature in the same season, while year's 2002, and 2011 experienced reduced glacial melt in post-monsoon and monsoon periods due to decreasing meteorological observations. Some conclusions even avoid temperature and precipitation trends, suggesting localized events responsible for changes in glacial melt inflow e.g. in the year 2017.

The resultant glacial melt patterns somewhat match the area determination of Dona Lake (Figure 4.2), where a small change can be seen during 2005-2015, but there has been a rapid expansion since then.

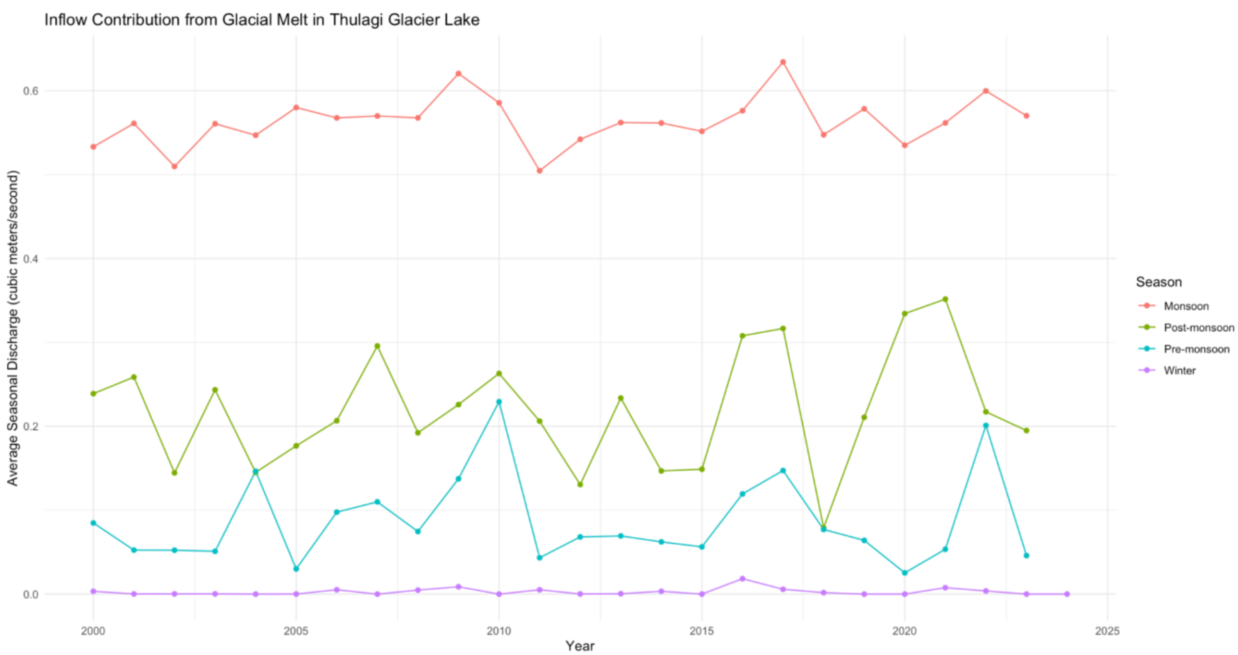


Figure 4.5: Inflow Contribution from Glacial Melt in Thulagi Glacier Lake (Dona Lake)

Precipitation in Nepal is significantly influenced by the Indian monsoon and westerlies (Shrestha, 2000; Sigdel & Ikeda, 2012; Haritashya et al., 2018). Analysis of annual precipitation trends from meteorological stations within the Marsyangdi River Basin reveals that central stations exhibit an increasing trend, whereas stations near basin boundaries show a slight decline (Khadka & Pathak, 2016). As Yao et al (2012) indicate a weakening of the Indian monsoon and a strengthening of the westerlies in the region, influences in precipitation patterns can therefore be attributed to the complex interaction of the rugged Himalayan terrain and climatic systems responsible for rainfall in Nepal.

Glacial melt in 2011 suggests a strong relation between monsoon and pre-monsoon inflow with temperature trends rather than precipitation trends, as a weak glacial melt resulted due to reduced seasonal temperature despite an increase in rainfall. The next year, a similar finding formed a directly proportional relationship between post-monsoonal glacial melt and temperature. Increased monsoonal rainfall in 2013 again plunged as post-monsoonal inflow displayed a similar trend, suggesting a correlation between monsoonal rainfall and post-monsoonal inflow due to the melt of summer accumulation glaciers in post-monsoonal temperatures.

In 2017, two significant glacier calving events at the Thulagi Glacier terminus led to a sharp rise in inflow due to glacial melt, with an estimated total calved volume of 880,000 m^3 (Watson et al., 2020). These mass movements were triggered by the flotation of subaqueous ice and the expansion of crevasses at the glacier terminus. During autumn, the study recorded near-record cold lake temperatures, which dropped by almost 2°C. Our research supports these findings, showing a steady decline in post-monsoon temperatures from 2016 to 2017 and a rapid decline from 2017 to 2018. Additionally, the warmest mean lake temperatures observed with ASTER and Landsat Thermal Imagery in September 2015 (10.7 and 10.8°C) explain the steady crest to the following year in (Annex F), which we hypothesize could have contributed to the initiation of the calving events.

The Marsyangdi River received more than double the yearly rainfall of 300 mm in 2021 (Pradhan et al., 2022). Record high post-monsoonal temperatures and glacial melt can be seen in (Figure 4.5) as flooding events across the Tall village and Dharapani area were reported during monsoon season. The following year, we see a high inflow contribution in pre-monsoon and monsoon seasons due to the respective temperature increase despite a low annual rainfall. This glacial behavior suggests that temperature has a higher correlation with inflow contribution than precipitation, confirming our estimation from above.

As all glacial melt enters the Dona Lake, a relationship between the area of the lake and inflow can be devised. The peak discharge rates associated with the years following 2015 match the notable events during those periods in the above-mentioned studies as we see a rapid retreat of the Thulagi glacier. Also, as high elevation temperatures have rapidly risen in recent years (0.76 C during the last 45 years) (Alexander, 2016), an increase in temperature-driven melting could have increased melt patterns in recent years. Likewise, with an increase in forest fire frequency and area in recent years (Matin et al., 2017; Bhusal & Mandal, 2020), the impact of transboundary travel of black carbon on glacial melt cannot be looked over especially as the spatial distribution of aerosols is not well known (Rose, 2012; Hou et al., 2023).

CHAPTER V: CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Analyzing the evolution of PDGLs in Nepal since the 1980s reveals that six lakes —Imja, Lower Barun, Thulagi, Tsho Rolpa, Chamlang, and Lumding Tsho — are expanding more rapidly than others, with a range of 0.046 - 0.46 sq. km change in a decade. Two smaller unnamed lakes are also exhibiting expansion whereas the remaining have either remained constant or reduced in size. The distance from the lake to the moraine dam is a crucial parameter in determining the risk posed by some lakes, therefore studies of internal seepage into embankments and their hydrostatic potential are crucial in identifying associated threats. Lake-lowering activities have reduced some of the associated risks from GLOFs but they have not been completely eliminated. As glaciers continue to retreat, the seasonal variability in streamflow due to glacial melt is expected to increase, with potential implications for water availability and management. Efforts should therefore focus on rapidly identifying threats and implementing adaptive measures in response to climate change driven impacts in the high-altitude Himalayas.

MODSNOW modeled glacial melt patterns of Thulagi glacier reveal distinctive seasonal and annual variations significantly influenced by climatic variables. Glacial melt intensity is the highest in Monsoon followed by post-monsoon, pre-monsoon, and winter seasons, similar to temperature gradients in the same period. Rugged landforms in high-altitude areas affect local variation in precipitation patterns, generating variability in glacial melt rates within close proximity. Results from Mann Kendall test conclude a statistically insignificant increasing and decreasing trend in glacial melt rates during Monsoon & winter, and Pre-monsoon & post-monsoon seasons respectively. Frequent flooding events and glacial calving in the Marsyangdi River basin and Thulagi Glacier Lake during recent years underscore the importance of carrying out climate-related investigations in the river basin and directing efforts for executing National Adaptation Plans (NAP) and Local Adaptation Plans (LAP) in Tal village, Dharapani area.

5.2 Recommendations

Given that all 21 PDGLs exhibited fluctuations, thorough investigations are required to understand their behavior and mitigate potential hazards. Establishing additional meteorological stations at vulnerable regions and accounting for missing hydrological data by employing advanced modeling techniques are advised to enhance reliability and minimize data gaps. Dona Lake has yet to be thoroughly researched, particularly in terms of the meteorological processes and seasonal patterns affecting it. Hence, employing frequently used hydrological models would provide crucial and accurate insights into the lake dynamics of the glacier lake. Comparing results from the MODSNOW tool against other observed data could further enhance our understanding of the accuracy of its predictions in the context of the Nepalese Himalayas and the HKH region.

REFERENCES

- Adhikari, S., Marshall, S. J., & Huybrechts, P. (2011). "On characteristic timescales of glacier AX010 in the Nepalese Himalaya." *Bulletin of Glaciological Research*, 29, 19-29.
- Aðalgeirsdóttir, G., Magnússon, E., Pálsson, F., Thorsteinsson, T., Belart, J., Jóhannesson, T., … & Björnsson, H. (2020). "Glacier changes in Iceland from∼ 1890 to 2019." *Frontiers in Earth Science*, 8, 523646. *DOI:10.3389/feart.2020.523646* (Accessed: 19 February 2024)
- Ageta, Y. (1983). "Characteristics of mass balance of the summer-accumulation type glacier in the Nepal Himalaya (I) Mass balance of Glacier AX010 in east Nepal." *Journal of the Japanese Society of Snow and Ice*, 45(2), 81-90.
- Ageta, Y., & Higuchi, K. (1984). "Estimation of Mass Balance Components of a Summer-Accumulation Type Glacier in the Nepal Himalaya." *Annals of Geography*, 66(3), 249–255.
- Alexander, L. V. (2016). "Global observed long-term changes in temperature and precipitation extremes: A review of progress and limitations in IPCC assessments and beyond." *Weather and Climate Extremes*, 11, 4–16.
- Ashraf, A., Iqbal, M. B., Mustafa, N., Naz, R., & Ahmad, B. (2021). "Prevalent risk of glacial lake outburst flood hazard in the Hindu Kush–Karakoram–Himalaya region of Pakistan." *Environmental Earth Sciences*, 80(12), 451. *DOI:10.1007/s12665-021-09740-1* (Accessed: 19 February 2024)
- Attaullah, H., Khan, A., Khan, M., Khan, F., Ali, S., Masud, T., & Iqbal, M. S. (2022). "The Karakoram Anomaly: Validation through Remote Sensing Data, Prospects and Implications." *Water*, 14(19), 3157. *DOI:10.3390/w14193157* (Accessed: 17 October 2023)
- Awasthi, R. P., & Owen, J. S. (2020). "Observed climate extreme in Nepal." *The Geographic Base*, 7, 1-14.
- Bajracharya, S. R. (2010). "Glacial lake outburst flood disaster risk reduction activities in Nepal." *International Journal of Erosion Control Engineering*, 3(1), 92-101.
- Bajracharya, S. R., Maharjan, S. B., Shrestha, F., Sherpa, T. C., Wagle, N., Shrestha, A. B. (2020). "Inventory of glacial lakes and identification of potentially dangerous glacial lakes

in the Koshi, Gandaki, and Karnali River Basins of Nepal, the Tibet Autonomous Region of China, and India." International Centre for Integrated Mountain Development (ICIMOD); United Nations Development Programme (UNDP), Research Report. *DOI:10.53055/ICIMOD.773* (Accessed: 6 February 2024)

- Bajracharya, S. R., & Mool, P. (2009). "Glaciers, glacial lakes and glacial lake outburst floods in the Mount Everest region, Nepal." *Annals of Glaciology*, 50(53), 81-86.
- Baral, P., Kayastha, R. B., Immerzeel, W. W., Pradhananga, N. S., Bhattarai, B. C., Shahi, S., ... & Mool, P. K. (2014). "Preliminary results of mass-balance observations of Yala Glacier and analysis of temperature and precipitation gradients in Langtang Valley, Nepal." *Annals of Glaciology*, 55(66), 9-14.
- Bazai, N. A., Cui, P., Carling, P. A., Wang, H., Hassan, J., Liu, D., ... & Jin, W. (2021). "Increasing glacial lake outburst flood hazard in response to surge glaciers in the Karakoram." *Earth-Science Reviews*, 212, 103432. *DOI:10.1016/j.earscirev.2020.103432* (Accessed: 2 March 2024)
- Benn, D. I., Bolch, T., Hands, K., Gulley, J., Luckman, A., Nicholson, L. I., ... & Wiseman, S. (2012). "Response of debris-covered glaciers in the Mount Everest region to recent warming, and implications for outburst flood hazards." *Earth-Science Reviews*, 114(1-2), 156-174.
- Bhattacharya, A., Bolch, T., Mukherjee, K., King, O., Menounos, B., Kapitsa, V., ... & Yao, T. (2021). "High Mountain Asian glacier response to climate revealed by multi-temporal satellite observations since the 1960s." *Nature communications*, 12(1), 4133. *DOI:10.1038/s41467-021-24180-y* (Accessed: 5 February 2024)
- Bliss, A., Hock, R., & Radić, V. (2014). "Global response of glacier runoff to twenty-first century climate change." *Journal of Geophysical Research: Earth Surface*, 119(4), 717-730.
- Bolch, T., Kulkarni, A., Kääb, A., Huggel, C., Paul, F., Cogley, J. G., … & Stoffel, M. (2012). "The state and fate of Himalayan glaciers." *Science*, 336(6079), 310–314.
- Bolch, T., Shea, J. M., Liu, S., Azam, F. M., Gao, Y., Gruber, S., ... & Zhang, Y. (2019). "Status and change of the cryosphere in the extended Hindu Kush Himalaya region." *The Hindu Kush Himalaya assessment: Mountains, climate change, sustainability, and people*, 1, 209-255.

- Boyd, B.L., Anderson, J.B.,Wellner, J.S., & Fernández, R.A. (2008). "The sedimentary record of glacial retreat, Marinelly fjord, Patagonia: regional correlations and climate ties." *Marine Geology*, 255, 165–178.
- Braithwaite, R.J. (1995). "Positive degree-day factors for ablation on the Greenland ice sheet studied by energy-balance modelling." *Journal of Glaciology*, 41(137), 153–160.
- Brun, F., Berthier, E., Wagnon, P., Kääb, A., & Treichler, D. (2017). "A spatially resolved estimate of High Mountain Asia glacier mass balances from 2000 to 2016." *Nature Geoscience*, 10(9), 668-673.
- Brun, F., Wagnon, P., Berthier, E., Jomelli, V., Maharjan, S. B., Shrestha, F., & Kraaijenbrink, P. D. A. (2019). "Heterogeneous influence of glacier morphology on the mass balance variability in High Mountain Asia." *Journal of Geophysical Research: Earth Surface*, 124(6), 1331-1345.
- Budhathoki, K. P., Bajracharya, O. R., & Pokharel, B. K. (2010). "Assessment of Imja Glacier Lake outburst flood (GLOF) risk in Dudh Koshi River Basin using remote sensing techniques." *Journal of Hydrology and Meteorology*, 7(1), 75-91.
- Burton, J. W., Chambers, F. B., Sincavage, R., & Cross, M. D. (2022). "Analysis of glacial lake outburst flood terrain and sedimentary deposits in Valle Soler, Northern Patagonia Icefield." *Physical Geography*, 43(3), 333-349.
- Byers, A. C., Chand, M. B., Lala, J., Shrestha, M., Byers, E. A., & Watanabe, T. (2020). "Reconstructing the history of glacial lake outburst floods (GLOF) in the Kanchenjunga conservation area, East Nepal: An interdisciplinary approach." *Sustainability*, 12(13), 5407. *DOI:10.3390/su12135407* (Accessed: 10 February 2024)
- Byers, A. C., Somos-Valenzuela, M., Shugar, D. H., McGrath, D., Chand, M. B., & Avtar, R. (2024). "Brief communication: An ice-debris avalanche in the Nupchu Valley, Kanchenjunga Conservation Area, eastern Nepal." *The Cryosphere*, 18(2), 711-717.
- Casassa, G., Wendt, J., Wendt, A., López, P., Schuler, T., H-gerd, … & Andrés, R. (2010). "Outburst floods of glacial lakes in Patagonia: is there an increasing trend?" *Geophysical Research Abstracts*, 12, 12821. *DOI:2010EGUGA..1212821C* (Accessed: 23 April 2024)
- Chen, H., Zhao, J., Liang, Q., Maharjan, S. B., & Joshi, S. P. (2022). "Assessing the potential impact of glacial lake outburst floods on individual objects using a high-performance hydrodynamic model and open-source data." *Science of The Total*

Environment, 806, 151289. *DOI:10.1016/j.scitotenv.2021.151289* (Accessed: 10 February 2019)

- Christensen, J. H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., … & Whetton, P. (2007). "Regional Climate Projections." Working Group I, Fourth Assessment Report of the Intergovernmental Panel on Climate Change, *The Physical Science Basis*. *http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter11.pdf* (Accessed: 27 January 2024)
- Dahal, K. R., & Hagelman III, R. (2011). "People's risk perception of glacial lake outburst flooding: a case of Tsho Rolpa Lake, Nepal." *Environmental Hazards*, 10(2), 154-170.
- Dell, R., Carr, R., Phillips, E., & Russell, A. J. (2019). "Response of glacier flow and structure to proglacial lake development and climate at Fjallsjökull, south-east Iceland." *Journal of Glaciology*, 65(250), 321-336.
- Dimri, A. P. (2021). "Decoding the Karakoram anomaly." *Science of The Total Environment*, 788, 147864. *DOI:10.1016/j.scitotenv.2021.147864* (Accessed: 19 February 2024)
- Ding, Y., Zhang, S., Zhao, L., Li, Z., & Kang, S. (2019). "Global warming weakening the inherent stability of glaciers and permafrost." *Science Bulletin*, 64(4), 245-253.
- DHM. (2017). "Observed climatic trend analysis in the districts and physiographic zones of Nepal (1971-2014)." *Department of Hydrology and Meteorology, Kathmandu*. *https://www.dhm.gov.np/* (Accessed: 13 December 2023)
- DHM. (2024). "Weather Stations." Department of Hydrology and Meteorology, Kathmandu. *https://www.dhm.gov.np/* (Accessed: 12 February 2024)
- Dokulil, M. T., Teubner, K., Jagsch, A., Nickus, U., Adrian, R., Straile, D., ... & Padisák, J. (2010). "The impact of climate change on lakes in Central Europe" *Springer Netherlands, Aquatic Ecology Series*, 4, 387-409.
- Dubey, S., Sattar, A., Gupta, V., Goyal, M. K., Haritashya, U. K., & Kargel, J. S. (2024). "Transboundary hazard and downstream impact of glacial lakes in Hindu-Kush Karakoram Himalayas." *Science of The Total Environment*, 914, 169758. *DOI:10.1016/j.scitotenv.2023.169758* (Accessed: 10 December 2024)

- Engelhardt, M., Schuler, T. V., & Andreassen, L. M. (2014). “Contribution of snow and glacier melt to discharge for highly glacierised catchments in Norway.” *Hydrology and Earth System Sciences*, 18(2), 511-523.
- Etourneau, J., Sgubin, G., Crosta, X., Swingedouw, D., Willmott, V., Barbara, L., ... & Kim, J. H. (2019). “Ocean temperature impact on ice shelf extent in the eastern Antarctic Peninsula.” *Nature Communications*, 10(1), 304. *DOI:10.1038/s41467-018-08195-6* (Accessed: 13 December 2023)
- Farinotti, D., Huss, M., Fürst, & Pandit, J.J. (2019) “A consensus estimate for the ice thickness distribution of all glaciers on Earth.” *Nature Geoscience*, 12, 168–173.
- Fischer, E. M., & Knutti, R. (2015). “Anthropogenic contribution to global occurrence of heavy-precipitation and high-temperature extremes.” *Nature Climate Change*, 5(6), 560-564.
- Fujita, K., Takeuchi, N., & Seko, K. (1998). “Glaciological observations of Yala Glacier in Langtang Valley, Nepal Himalayas, 1994 and, B.: *Glacier Res*, 16, 75-8.
- Gafurov, A., Lüdtke, S., Unger-Shayesteh, K., Vorogushyn, S., Schöne, T., Schmidt, S., … & Merz, B. (2016). “MODSNOW-Tool: an operational tool for daily snow cover monitoring using MODIS data.” *Environmental Earth Sciences*, 75, 1-15.
- Gardelle, J., Arnaud, Y., & Berthier, E. (2011). “Contrasted evolution of glacial lakes along the Hindu Kush Himalaya mountain range between 1990 and 2009.” *Global Planetary Change*, 75(1-2), 47–55.
- Gonzalez, S., & Fortuny, D. (2018). “How robust are the temperature trends on the Antarctic Peninsula?” *Antarctic Science,* 30(5), 322-328.
- Gouli, M. R., Hu, K., Khadka, N., & Talchabhadel, R. (2023). “Hazard assessment of a pair of glacial lakes in Nepal Himalaya: unfolding combined outbursts of Upper and Lower Barun.” *Geomatics, Natural Hazards and Risk*, 14(1), 2266219. *DOI:10.1080/19475705.2023.2266219* (Accessed: 22 December 2023)
- Gusev, E. M., Nasonova, O. N., Kovalev, E. E., & Ayzel, G. V. (2019). “Impact of Possible Climate Change on Extreme Annual Runoff from River Basins Located in Different Regions of the Globe.” *Water Resources,* 46(S1), 126–136.
- Haritashya, U. K., Kargel, J. S., Shugar, D. H., Leonard, G. J., Strattman, K., Watson, C. S., ... & Regmi, D. (2018). “Evolution and controls of large glacial lakes in the Nepal

Himalaya." *Remote Sensing*, 10(5), 798. *DOI:10.3390/rs10050798* (Accessed: 18 October 2023)

- Hartmann, H., & Buchanan, H. (2014). "Trends in extreme precipitation events in the Indus River Basin and flooding in Pakistan." *Atmosphere-Ocean*, 52(1), 77-91.
- Higuchi, K. (1977). "Effect of Nocturnal Precipitation on the Mass Balance of the Rikha Samba Glacier, Hidden Valley, Nepal Glaciological Expedition of Nepal." *Journal of the Japanese Society of Snow and Ice*, 39, 43-49.
- Hipel, K.W. & McLeod, A.I., (1994). "Time Series Modelling of Water Resources and Environmental Systems." *ISBN:044489270-2* (Accessed: 11 April 2024)
- Hirsch, R.M., Slack, J.R. & Smith, R.A. (1982). "Techniques of Trend Analysis for Monthly Water Quality Data." *Water Resources Research*, 18, 107-121.
- Hock, (2003). "Temperature index melt modelling in mountain areas." *Journal of Hydrology*, 282(1–4), 104–115.
- Hock, R. (1998). "Modelling of glacier melt and discharge." Doctoral dissertation, ETH Zurich. *https://www.research-collection.ethz.ch/bitstream/handle/20.500.11850/143428/eth-41026-01.pdf?sequence=1* (Accessed: 4 May 2024)
- Hou, Z., Li, Y., Zhang, L., Song, C., Lin, J., Zhou, C., ... & Gao, P. (2023). "The COVID-19 lockdown: a unique perspective into heterogeneous impacts of transboundary pollution on snow and ice darkening across the Himalayas." *PNAS nexus*, 2(6), 172-183.
- Huettmann, F., & Regmi, G. R. (2020). "Mountain landscapes and watersheds of the Hindu Kush-Himalaya (HKH) and their biogeography: a descriptive overview and introduction for 18 nations in the Anthropocene." *Hindu Kush-Himalaya Watersheds Downhill: Landscape Ecology and Conservation Perspectives*, 1, 3-23.
- Hulley, M., Watt, E., & Clarke, C. (2019). "Annual discharge trends for Canadian rivers." *International journal of river basin management*, 17(4), 423-434.
- Huss, M., & Hock, R. (2018). "Global-scale hydrological response to future glacier mass loss." *Nature Climate Change*, 8(2), 135-140.
- Immerzeel, W. W., Van Beek, L. P., & Bierkens, M. F. (2010). "Climate change will affect the Asian water towers." *Science*, 328(5984), 1382-1385.

- IPCC. (2018). “Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty” Intergovernmental Panel on Climate Change, Special Report, Summary for Policymakers. *https://www.ipcc.ch/site/assets/uploads/sites/2/2022/06/SPM_version_report_LR.pdf* (Accessed: 15 December 2023)
- IPCC. (2021). “Climate Change 2021: The Physical Science Basis” Intergovernmental Panel on Climate Change, Sixth Assessment Report (AR6). *https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_FullReport_small.pdf* (Accessed: 22 October 2023)
- Joshi, S., & Bhattarai, P. (2021). "Temporal Changes of Temperature, Snow Cover and Glacier Area of Lumding Tsho Lake Watershed." *Proceedings of 10th IOE Graduate Conference*, 10, 1346-1350.
- Juen, M., Mayer, C., Lambrecht, A., Han, H., & Liu, S. (2014). “Impact of varying debris cover thickness on ablation: a case study for Koxkar Glacier in the Tien Shan.” *The Cryosphere*, 8(2), 377-386.
- Kargel, J., Leonard, G., Regmi, D., Haritashya, U., Chand, M., Pradhan, S., ... & Huggel, C. (2015). “Glacier dynamics and outburst flood potential from the Imja and Thulagi Glacier-Lake systems (Nepal).” *EGU General Assembly Conference Abstracts*, 15554. *DOI:2015EGUGA..1715554K* (Accessed: 14 April 2024)
- Karki, R., ul Hasson, S., Gerlitz, L., Talchabhadel, R., Schickhoff, U., Scholten, T., & Böhner, J. (2020). “Rising mean and extreme near-surface air temperature across Nepal.” *International Journal of Climatology*, 40(4), 2445-2463.
- Kayastha, R. B. (2010). “Climate Change Impacts and Adaptation in the Nepalese Himalayas.” *Linnaeus Eco-Tech*, l, 756-765.
- Kayastha, R. B., Steiner, N., Kayastha, R., Mishra, S. K., & McDonald, K. (2020). “Comparative Study of Hydrology and Icemelt in Three Nepal River Basins Using the Glacio-Hydrological Degree-Day Model (GDM) and Observations From the Advanced Scatterometer (ASCAT).” *Frontier Earth Science*, 7, 354. *DOI:10.3389/feart.2019.00354* (Accessed: 22 February 2024)

- Khadka, D., & Pathak, D. (2016). "Climate change projection for the marsyangdi river basin, Nepal using statistical downscaling of GCM and its implications in geodisasters." *Geoenvironmental Disasters*, 3(1), 1-15.
- Khadka, N., Chen, X., Sharma, S., & Shrestha, B. (2023). "Climate change and its impacts on glaciers and glacial lakes in Nepal Himalayas." *Regional Environmental Change*, 23(4), 143. *DOI:10.1007/s10113-023-02142-y* (Accessed: 18 November 2023)
- Khadka, N., Zhang, G., & Chen, W. (2019). "The state of six dangerous glacial lakes in the Nepalese Himalaya." *Terrestrial, Atmospheric and Oceanic Sciences*, 30(1), 63-72.
- Khan, G., Ali, S., Xiangke, X., Qureshi, J. A., Ali, M., & Karim, I. (2021). "Expansion of Shishper Glacier lake and recent glacier lake outburst flood (GLOF), Gilgit-Baltistan, Pakistan." *Environmental Science and Pollution Research*, 28, 20290-20298.
- Khanal, N. R., Mool, P. K., Shrestha, A. B., Rasul, G., Ghimire, P. K., Shrestha, R. B., & Joshi, S. P. (2015). "A comprehensive approach and methods for glacial lake outburst flood risk assessment, with examples from Nepal and the transboundary area." *International Journal of Water Resources Development*, 31(2), 219-237.
- Komori, J. (2008). "Recent expansions of glacial lakes in the Bhutan Himalayas." *Quaternary International*, 184(1), 177-186.
- Kraaijenbrink, P. D. A., Bierkens, M. F. P., Lutz, A. F., Immerzeel, W. W. (2017). "Impact of a global temperature rise of 1.5 degrees Celsius on Asia's glaciers." *Nature*, 549(7671), 257–260.
- Kulkarni, A. V., Shirsat, T. S., Kulkarni, A., Negi, H. S., Bahuguna, I. M., & Thamban, M. (2021). "State of Himalayan cryosphere and implications for water security." *Water Security*, 14, 100101. *DOI:10.1016/j.wasec.2021.100101* (Accessed: 3 March 2024)
- Lama, L., Kayastha, R. B., Maharjan, S. B., Bajracharya, S. R., Chand, M. B., & Mool, P. K. (2015). "Glacier area and volume changes of Hidden Valley, Mustang, Nepal from~ 1980s to 2010 based on remote sensing." *Proceedings of the International Association of Hydrological Sciences*, 368, 57-62.
- Lamsal, D., Sawagaki, T., Watanabe, T., & Byers, A. C. (2016). "Assessment of glacial lake development and prospects of outburst susceptibility: Chamlang South Glacier, eastern Nepal Himalaya." *Geomatics, Natural Hazards and Risk*, 7(1), 403-423.

- Lamsal, D., Sawagaki, T., Watanabe, T., & Sakai, A. (2013). "Evolution of supra-glacial ponds on a debris-covered Chamlang South Glacier, Nepal Himalaya to a potentially dangerous glacial lake." *American Geophysical Union*, 1, C33B-0709.
- Le Fort, P. (1975). "Himalayas: the collided range. Present knowledge of the continental arc." *American Journal of Science*, 275(1), 1-44.
- Li, W., Wang, W., Gao, X., Wang, X., & Wang, R. (2022). "Inventory and Spatiotemporal Patterns of Glacial Lakes in the HKH-TMHA Region from 1990 to 2020." *Remote Sensing*, 14(6), 1351. *DOI:10.3390/rs14061351* (Accessed: 15 February 2024)
- Li, Z., Huang, G., Wang, X., Han, J., & Fan, Y. (2016). "Impacts of future climate change on river discharge based on hydrological inference: A case study of the Grand River Watershed in Ontario, Canada." *Science of the Total Environment*, 548, 198-210.
- Linsbauer, A., Frey, H., Haeberli, W., Machguth, H., Azam, M. F., & Allen, S. (2016). "Modelling glacier-bed overdeepenings and possible future lakes for the glaciers in the Himalaya – Karakoram region." *Annals of Glaciology*, 57, 119–130.
- Lopez, P., Chevallier, P., Favier, V., Pouyaud, B., Ordenes, F., & Oerlemans, J. (2010). "A regional view of fluctuations in glacier length in southern South America." *Global and Planetary Change,* 71, 85–108.
- Mapscaling. (2023). "4 ways to calculate the area of polygons using QGIS" *https://mapscaping.com/4-ways-to-calculate-the-area-of-polygons-using-qgis/* (Accessed: 15 February 2024)
- Maskey, S., Kayastha, R. B., & Kayastha, R. (2020). "Glacial lakes outburst floods (GLOFs) modelling of Thulagi and lower Barun glacial lakes of Nepalese Himalaya." *Progress in Disaster Science*, 7, 100106. *DOI:10.1016/j.pdisas.2020.100106* (Accessed: 9 September 2023)
- Miller, J. D., Immerzeel, W. W., & Rees, G. (2012). "Climate change impacts on glacier hydrology and river discharge in the Hindu Kush–Himalayas." *Mountain Research and Development*, 32(4), 461-467.
- Molden, D. J., Shrestha, A. B., Immerzeel, W. W., Maharjan, A., Rasul, G., Wester, P., ... & Nepal, S. (2022). "The great glacier and snow-dependent rivers of Asia and climate change: Heading for troubled waters." *Water security under climate change*, 1, 223-250.

- Mool, P. K., Maskey, P. R., Koirala, A., Joshi, S. P., Lizong, W., Shrestha, A. B., ... & Shrestha, R. B. (2011). "Glacial lakes and glacial lake outburst floods in Nepal." International Centre for Integrated Mountain Development (ICIMOD), Kathmandu. *https://www.gfdrr.org/sites/default/files/publication/final_report_Glacial%20Lakes%20Outburst%20Floods%20Nepal.pdf* (Accessed: 10 February 2024)
- Moyer, A. N., Moore, R. D., & Koppes, M. N. (2016). "Streamflow response to the rapid retreat of a lake-calving glacier." *Hydrological Processes*, 30(20), 3650-3665.
- NASA. (2023). "What is Climate Change?" National Aeronautics and Space Administration, Global Climate Change. *https://climate.nasa.gov/what-is-climate-change/* (Accessed: 17 October 2023)
- Nie, Y., Sheng, Y., Liu, Q., Liu, L., Liu, S., Zhang, Y., & Song, C. (2017). "A regional-scale assessment of Himalayan glacial lake changes using satellite observations from 1990 to 2015." *Remote Sensing of Environment*, 189, 1-13.
- Nie, Y., Zhang, Y., Liu, L., & Zhang, J. (2010). "Glacial change in the vicinity of Mt. Qomolangma (Everest), Central High Himalayas since 1976." *Journal of Geographical Sciences*, 20, 667-686.
- Ojha, S., Fujita, K., Asahi, K., Sakai, A., Lamsal, D., Nuimura, T., & Nagai, H. (2016). "Glacier area shrinkage in eastern Nepal Himalaya since 1992 using high-resolution inventories from aerial photographs and ALOS satellite images." *Journal of Glaciology*, 62(233), 512-524.
- O'Neill, A. (2021). "Analytical Hierarchical Modeling of Glacial Lake Outburst Flood Potential in the Khumbu Region, Nepal." Doctoral dissertation, Appalachian State University. *https://libres.uncg.edu/ir/asu/f/O'Neill_Alex_May%202021_Thesis.pdf/* (Accessed: 1 May 2024)
- Ono, Y. (1985). "Recent fluctuations of the Yala (Dakpatsen) Glacier, Langtang Himal, reconstructed from annual moraine ridges." *ZEITSCHRIFT FOR GLETSCHERKUNDE UND GLAZIALGEOLOGIE*, 21, 251-258.
- Owen, L. A., & Benn, D. I. (2005). "Equilibrium-line altitudes of the Last Glacial Maximum for the Himalaya and Tibet: an assessment and evaluation of results." *Quaternary International*, 138, 55-78.

- Palazzi, E., von Hardenberg, J., Terzago, S., & Provenzale, A. (2015). "Precipitation in the Karakoram-Himalaya: a CMIP5 view." *Climate Dynamics,* 45, 21-45.
- Pandey, P., Ali, S. N., & Champati Ray, P. K. (2021). "Glacier-glacial lake interactions and glacial lake development in the central Himalaya, India (1994–2017)." *Journal of Earth Science,* 32, 1563–1574.
- Pandey, R. (2016). "Dynamics of the Himalayan Climate: A Study of the Kaligandaki Basin, Nepal." *Pertanika Journal of Social Sciences & Humanities*, 24(2), 737-756.
- Pant, S. R., & Reynolds, J. M. (2000). "Application of electrical imaging techniques for the investigation of natural dams: an example from the Thulagi Glacier Lake, Nepal." *Journal of Nepal Geological Society*, 22, 211-218.
- Parajuli, A., Devkota, L. P., Adhikari, T. R., Dhakal, S., & Kayastha, R. B. (2015). "Impact of Climate change on river discharge and rainfall pattern: a case study from Marshyangdi River basin, Nepal." *Journal of Hydrology and Meteorology,* 9(1), 60-73.
- Parajuli, A., Chand, M. B., Kayastha, R. B., Shea, J. M., & Mool, P. K. (2015). "Modified temperature index model for estimating the melt water discharge from debris-covered Lirung Glacier, Nepal." *Proceedings of the International Association of Hydrological Sciences,* 368, 409-414.
- Paul, F., Kääb, A., Maisch, M., Kellenberger, T., & Haeberli, W. (2002). "The new remote-sensing-derived Swiss glacier inventory: I. Methods." *Annals of Glaciology*, 34, 355-361.
- Pelto, M. (2016). "Thulagi Glacier, Nepal Retreat and GLOF Potential." *A*dvancing Earth and Space Sciences., Blogosphere. *https://blogs.agu.org/fromaglaciersperspective/2016/11/07/thulagi-glacier-nepal-retreat-glof-potential/* (Accessed: 28 February 2024)
- Pepin, N., Bradley, R. S., Diaz, H. F., Baraer, M., Caceres, E. B., Forsythe, N., … & Yang, D. Q. (2015). "Elevation-dependent warming in mountain regions of the world." *Nature Climate Change*, 5(5), 424–430.
- Peppa, M. V., Maharjan, S. B., Joshi, S. P., Xiao, W., & Mills, J. P. (2020). "Glacial Lake evolution based on remote sensing time series: A case study of Tsho Rolpa in Nepal." *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 3, 633-639.

- Poudel, A., Cuo, L., Ding, J., & Gyawali, A. R. (2020). "Spatio-temporal variability of the annual and monthly extreme temperature indices in Nepal." *International Journal of Climatology*, 40(11), 4956-4977.
- Pradhan, A.M.S., Bista, A., Maharjan, M., Maharjan, B., & Gadtaula, M. (2022). "Flood Hazard Mapping and Vulnerability Analysis of Building structures at Chame and Taal Gaon area, Manang District." *WRRDC Research Letter*, 20, 1-2.
- Pradhananga, N. S., Kayastha, R. B., Bhattarai, B. C., Adhikari, T. R., Pradhan, S. C., Devkota, L. P., ... & Mool, P. K. (2014). "Estimation of discharge from Langtang River basin, Rasuwa, Nepal, using a glacio-hydrological model." *Annals of Glaciology*, 55(66), 223-230.
- Putnam, A. E., & Broecker, W. S. (2017). "Human-induced changes in the distribution of rainfall." *Science Advances*, 3(5), e1600871. *DOI:10.1126/sciadv.160087* (Accessed: 28 March 2024)
- Rabassa, J. (2009). "Impact of Global Climate Change on Glaciers and Permafrost of South America, with Emphasis on Patagonia, Tierra del Fuego, and the Antarctic Peninsula." *Natural Hazards and Human-Exacerbated Disasters in Latin America*, 13, 415–438.
- Racoviteanu, A. E., Armstrong, R., & Williams, M. W. (2013). "Evaluation of an ice ablation model to estimate the contribution of melting glacier ice to annual discharge in the Nepal Himalaya." *Water Resources Research,* 49(9), 5117-5133.
- Racoviteanu, A. E., Glasser, N. F., Robson, B. A., Harrison, S., Millan, R., Kayastha, R. B., & Kayastha, R. (2022). "Recent evolution of glaciers in the Manaslu region of Nepal from satellite imagery and UAV data (1970–2019)." *Frontiers in Earth Science*, 9, 767317. *DOI:10.3389/feart.2021.767317* (Accessed: 2 February 2023)
- Rahman, K., da Silva, A. G., Tejeda, E. M., Gobiet, A., Beniston, M., & Lehmann, A. (2015). "An independent and combined effect analysis of land use and climate change in the upper Rhone River watershed, Switzerland." *Applied Geography*, 63, 264-272.
- Rana, B., Shrestha, A. B., Reynolds, J. M., & Aryal, R. (2000). "Hazard assessment of the Tsho Rolpa Glacier Lake and ongoing." *Journal of Nepal Geological Society*, 22, 563-570.
- Richardson, S. D., & Reynolds, J. M. (2000). "An overview of glacial hazards in the Himalayas." *Quaternary International*, 65, 31-47.

- Rick, B., McGrath, D., Armstrong, W., & McCoy, S. W. (2022). "Dam type and lake location characterize ice-marginal lake area change in Alaska and NW Canada between 1984 and 2019." *The Cryosphere*, 16, 297–314.
- Robson, B. A., Nuth, C., Nielsen, P. R., Girod, L., Hendrickx, M., & Dahl, S. O. (2018). "Spatial variability in patterns of glacier change across the Manaslu Range, Central Himalaya." *Frontiers in Earth Science*, 6, 12. *DOI:10.3389/feart.2018.00012* (Accessed: 26 October 2023)
- Rose, E. (2012). "The ABCs of Governing the Himalayas in response to Glacial Melt: Atmospheric BrownClouds, Black Carbon, and Regional Cooperation." *Sustainable Development Law & Policy*, 12(2), 33-37.
- Rounce, D. R., McKinney, D. C., Lala, J. M., Byers, A. C., & Watson, C. S. (2016). "A new remote hazard and risk assessment framework for glacial lakes in the Nepal Himalaya." *Hydrology and Earth System Sciences*, 20(9), 3455–3475.
- Sen, P.K. (1968). "Estimates of the Regression Coefficient based on Kendall's Tau." *Journal of the American Statistical Association*, 63, 1379-1389.
- Shea, J. M., & Immerzeel, W. W. (2016). "An assessment of basin-scale glaciological and hydrological sensitivities in the Hindu Kush–Himalaya." *Annals of Glaciology*, 57(71), 308-318.
- Sherry, J., & Curtis, A. (2017). "At the intersection of disaster risk and religion: Interpretations and responses to the threat of Tsho Rolpa glacial lake." *Environmental Hazards*, 16(4), 314-329.
- Shrestha, M. L. (2000). "Interannual variation of summer monsoon rainfall over Nepal and its relation to Southern Oscillation Index." *Meteorology and Atmospheric Physics*, 75(1), 21-28.
- Shrestha, A. B., & Aryal, R. (2010). "Climate change in Nepal and its impact on Himalayan glaciers." *Regional Environmental Change*, 11(S1), 65–77.
- Shrestha, B. B., & Nakagawa, H. (2013). "Assessment of potential outburst floods from the Tsho Rolpa glacial lake in Nepal." *Natural Hazards*, 71(1), 913–936.
- Shrestha, N. M., & Balla, M. K. (2011). "Temporal change detection of Lumding Tsho glacial lake in Dudh-Koshi basin, Nepal." *Journal of Environmental Research and Development*, 5(3A), 795-800.

- Shrestha, R., Kayastha, R. B., & Kayastha, R. (2020). “Effect of debris on seasonal ice melt (2016-2018) on Ponkar Glacier, Manang, Nepal.” *Sciences in Cold and Arid Regions*, 12(5), 261-271.
- Shugar, D. H., Burr, A., Haritashya, U. K., Kargel, J. S., Watson, C. S., Kennedy, M. C., … & Strattman, K. (2020). “Rapid worldwide growth of glacial lakes since 1990.” *Nature Climate Change*, 10(10), 939-945.
- Sinergise. (n.d.). “NDWI Normalized Difference Water Index.” Sentinel Hub Custom Scripts. *https://custom-scripts.sentinel-hub.com/custom-scripts/sentinel-2/ndwi/* (Accessed: 26 November 2023)
- Sigdel, M., & Ikeda, M. (2012). “Seasonal contrast in precipitation mechanisms over Nepal deduced from relationship with the large-scale climate patterns.” *Nepal Journal of Science and Technology*, 13(1), 115-123.
- Singh, H., Varade, D., de Vries, M. V. W., Adhikari, K., Rawat, M., Awasthi, S., & Rawat, D. (2023). “Assessment of potential present and future glacial lake outburst flood hazard in the Hunza valley: A case study of Shisper and Mochowar glacier.” *Science of The Total Environment*, 868, 161717. *DOI:10.1016/j.scitotenv.2023.161717* (Accessed: 2 November 2023)
- Staines, K. E., Carrivick, J. L., Tweed, F. S., Evans, A. J., Russell, A. J., Jóhannesson, T., & Roberts, M. (2015). “A multi-dimensional analysis of pro-glacial landscape change at Sólheimajökull, southern Iceland.” *Earth Surface Processes and Landforms*, 40(6), 809-822.
- Stumm, D., Joshi, S. P., Gurung, T. R., & Silwal, G. (2021). "Mass balances of Yala and Rikha Samba glaciers, Nepal, from 2000 to 2017" *Earth System Science Data*, 13, 3791–3818.
- Szabo, S., Gácsi, Z., & Balazs, B. (2016). “Specific features of NDVI, NDWI, and MNDWI as reflected in land cover categories.” *Acta Geographica Debrecina. Landscape & Environment Series*, 10(3-4), 194-202.
- Thakuri, S., Salerno, F., Bolch, T., Guyennon, N., & Tartari, G. (2016). “Factors controlling the accelerated expansion of Imja Lake, Mount Everest region, Nepal.” *Annals of Glaciology*, 57(71), 245-257.

- Thakuri, S., Dahal, S., Shrestha, D., Guyennon, N., Romano, E., Colombo, N., & Salerno, F. (2019). “Elevation-dependent warming of maximum air temperature in Nepal during 1976–2015.” *Atmospheric Research*, 228, 261-269.
- U.S.G.S. (2015). “Landsat—Earth observation satellites” *U.S. Geological Survey Fact Sheet 2015*, 3081, 4. *DOI:10.3133/fs20153081* (Accessed: 21 October 2023)
- Walder, J. S., & Costa, J. E. (1996). “Outburst floods from glacier-dammed lakes: The effect of mode of lake drainage on flood magnitude.” *Earth Surface Processes and Landforms*, 21(8), 701-723.
- Wang, S., Che, Y., & Xinggang, M. (2020). “Integrated risk assessment of glacier lake outburst flood (GLOF) disaster over the Qinghai–Tibetan Plateau (QTP).” *Landslides*, 17, 2849-2863.
- Wang, X., Siegert, F., Zhou, A. G., & Franke, J. (2013). “Glacier and glacial lake changes and their relationship in the context of climate change, Central Tibetan Plateau 1972–2010.” *Global and Planetary Change*, 111, 246-257.
- Wang, X., Liu, S. Y., Mo, H. W., Yao, X., Jiang, Z., & Guo, W. Q. (2011). “Expansion of glacial lakes and its implication for climate changes in the Chinese Himalaya.” *Acta Geographica Sinica*, 144(2), 104-110.
- Watanabe, T., Lamsal, D., & Ives, J. D. (2009). “Evaluating the growth characteristics of a glacial lake and its degree of danger of outburst flooding: Imja Glacier, Khumbu Himal, Nepal.” *Norwegian Journal of Geography*, 63(4), 255-267.
- Watson, C. S., Kargel, J. S., Shugar, D. H., Haritashya, U. K., Schiassi, E., & Furfaro, R. (2020). “Mass loss from calving in Himalayan proglacial lakes.” *Frontiers in Earth Science*, 7, 342. *DOI:10.3389/feart.2019.00342* (Accessed: 16 October 2023)
- WBG. (2021). “What is Climate Change?” World Bank Group, Climate Change Knowledge Portal For Development Practitioners and Policy Makers. *https://climateknowledgeportal.worldbank.org/overview* (Accessed: 22 October 2023)
- Wilhelm, B., Rapuc, W., Amann, B., Anselmetti, F. S., Arnaud, F., Blanchet, J., ... & Wirth, S. B. (2022). “Impact of warmer climate periods on flood hazard in the European Alps.” *Nature Geoscience*, 15(2), 118-123.

- Wilson, R., Glasser, N. F., Reynolds, J. M., Harrison, S., Anacona, P. I., Schaefer, M., & Shannon, S. (2018). “Glacial lakes of the Central and Patagonian Andes.” *Global and Planetary Change*, 162, 275-291.
- Wyss-Dunant, E. (1953). “The First Swiss Expedition to Mount Everest, 1952.” *Geographical Journal*, 1, 266-277.
- Yadav, M., Dimri, A. P., Mal, S., & Maharana, P. (2024). “Elevation-dependent precipitation in the Indian Himalayan Region.” *Theoretical and Applied Climatology*, 155(2), 815-828.
- Yao, T., Li, Z., Yang, W., Guo, X., Zhu, L., Kang, S., ... & Yu, W. (2010). “Glacial distribution and mass balance in the Yarlung Zangbo River and its influence on lakes.” *Chinese Science Bulletin*, 55, 2072-2078.
- Yao, T., Thompson, L., Yang, W., Yu, W., Gao, Y., Guo, X., ... & Joswiak, D. (2012). “Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings.” *Nature climate change*, 2(9), 663-667.
- You, Q. L., Ren, G. Y., Zhang, Y. Q., Ren, Y. Y., Sun, X. B., Zhan, Y. J., ... & Krishnan, R. (2017). “An overview of studies of observed climate change in the Hindu Kush Himalayan (HKH) region.” *Advances in Climate Change Research*, 8(3), 141-147.
- Zhang, Yong & Liu, Shiyin & Xie, Changwei & Ding, Yongjian. (2006). “Application of a degree-day model for the determination of contributions to glacier meltwater and runoff near Keqicar Baqi glacier, southwestern Tien Shan.” *Annals of Glaciology*, 43(1). 280-284.
- Zhang, W., Furtado, K., Wu, P., Zhou, T., Chadwick, R., Marzin, C., … & Sexton, D. (2021). “Increasing precipitation variability on daily-to-multiyear time scales in a warmer world.” *Science Advances*, 7(31), eabf8021. *DOI:10.1126/sciadv.abf8021* (Accessed: 19 September 2023)

ANNEXES

ANNEX A: Evolution of Potentially Dangerous Glacial Lakes (PDGLs) in Nepal

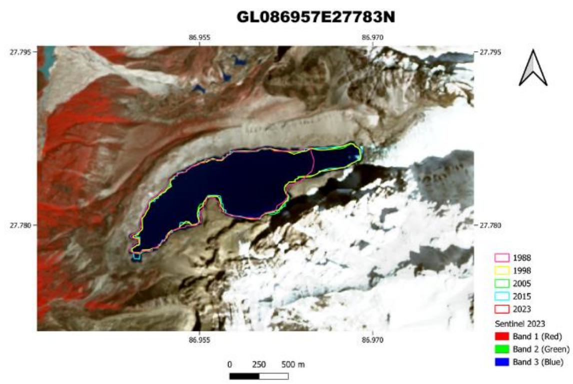
S.N	Glacial Lake	Date of Data Retrieval	Satellite Used	Obtained area (sq. km)	Average change per decade (sq. km)	Percentage Change
1	GL086612E27779N	1988/05/30	Landsat 5	0.616361	0.2133	138.45
		1999/04/27	Landsat 5	0.792461		
		2009/09/13	Landsat 5	1.042423		
		2019/09/09	Landsat 8	1.270966		
		2022/08/16	Landsat 8	1.469762		
2	GL086858E27687N	1989/11/09	Landsat 5	0.288546	0.0038	5.37
		1996/10/11	Landsat 5	0.295762		
		2004/10/17	Landsat 5	0.300686		
		2016/10/18	Landsat 8	0.303818		
		2023/10/30	Landsat 9	0.304066		
3	GL086957E27783N	1988/09/03	Landsat 5	0.735871	0.0134	7.32
		1998/09/15	Landsat 5	0.784957		
		2005/08/01	Landsat 5	0.786639		
		2015/07/12	Landsat 8	0.789113		
		2023/06/08	Landsat 9	0.78978		
4	GL086977E27711N	1989/06/02	Landsat 5	0.015101	0.0137	363.16
		1996/10/11	Landsat 5	0.038168		
		1996/10/11	Landsat 5	0.056441		
		2015/09/30	Landsat 8	0.06885		
		2023/10/22	Landsat 8	0.069942		
5	GL086925E27898N	1989/11/09	Landsat 5	0.610796	0.2757	180.57
		1995/10/25	Landsat 5	0.674624		
		2006/10/07	Landsat 5	0.93785		
		2015/09/30	Landsat 8	1.324059		
		2023/06/08	Landsat 9	1.713725		

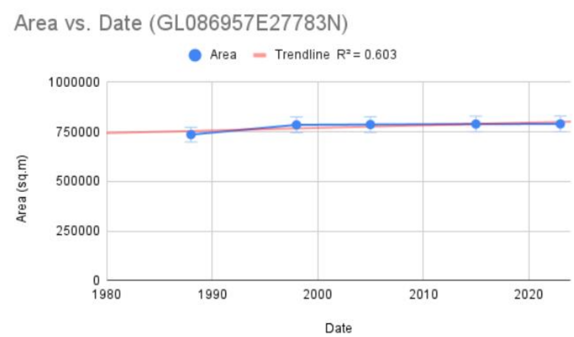
6	GL086935E27838N	1988/09/03	Landsat 5	0.304944	-0.004	-5.35
		1995/10/25	Landsat 5	0.288409		
		2005/11/05	Landsat 5	0.284249		
		2016/10/18	Landsat 8	0.289301		
		2023/10/14	Landsat 9	0.288604		
7	GL086928E27850N	1988/09/03	Landsat 5	0.45906	-0.0015	-1.38
		1995/10/25	Landsat 5	0.442989		
		2005/11/05	Landsat 5	0.438727		
		2016/10/18	Landsat 8	0.452648		
		2023/10/14	Landsat 9	0.452688		
8	GL086917E27832N	1988/09/03	Landsat 5	0.346587	-0.0092	-10.64
		1995/10/25	Landsat 5	0.360378		
		2005/11/05	Landsat 5	0.336559		
		2016/10/18	Landsat 8	0.321637		
		2023/10/14	Landsat 9	0.309694		
9	GL086476E27861N	1988/09/03	Landsat 5	1.400011	0.046	13.16
		1994/10/22	Landsat 5	1.434294		
		2009/09/13	Landsat 5	1.489239		
		2015/07/12	Landsat 8	1.545728		
		2023/06/08	Landsat 9	1.584388		
10	GL087596E27705N	1988/10/14	Landsat 5	0.021409	0.0009	17.0
		1998/10/17	Landsat 5	0.022018		
		2004/10/10	Landsat 5	0.023449		
		2016/10/27	Landsat 8	0.024962		
		2023/11/08	Landsat 9	0.025049		
11	GL087092E27798N	1987/12/06	Landsat 5	0.486236	0.4641	381.83
		1995/10/25	Landsat 5	0.752817		
		2006/02/09	Landsat 5	1.206963		
		2016/11/03	Landsat 8	1.854567		
		2023/10/22	Landsat 8	2.342859		

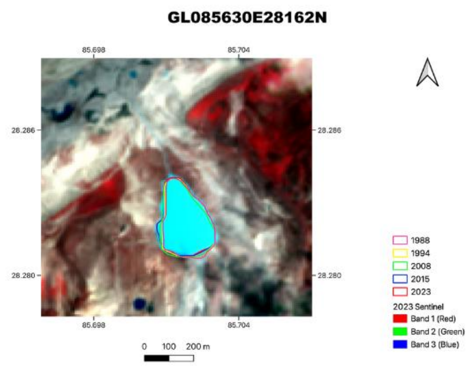
12	GL087749E27816N	1988/10/14	Landsat 5	0.180291	-0.0035	-7.80
		1994/10/31	Landsat 5	0.175652		
		2005/10/13	Landsat 5	0.163506		
		2015/09/30	Landsat 8	0.167725		
		2023/06/08	Landsat 9	0.166216		
13	GL087945E27781N	1988/10/14	Landsat 5	0.046566	-0.0025	-22.31
		1996/10/20	Landsat 5	0.043725		
		2005/10/13	Landsat 5	0.037591		
		2015/10/09	Landsat 8	0.036334		
		2023/06/09	Landsat 8	0.036177		
14	GL084485E28488N	1988/11/20	Landsat 5	0.672328	0.0807	48.05
		1996/10/09	Landsat 5	0.797021		
		2006/11/22	Landsat 5	0.887235		
		2015/09/28	Landsat 8	0.897852		
		2023/09/02	Landsat 8	0.995448		
15	GL085630E28162N	1988/09/26	Landsat 5	0.055884	0.0007	5.59
		1994/09/27	Landsat 5	0.057395		
		2008/11/04	Landsat 5	0.056821		
		2015/10/07	Landsat 8	0.058263		
		2023/11/22	Landsat 9	0.059008		
16	GL086958E27755N	1989/11/09	Landsat 5	0.50928	0.0864	67.91
		1995/09/23	Landsat 5	0.760096		
		2006/09/05	Landsat 5	0.848632		
		2015/09/30	Landsat 8	0.851619		
		2023/10/22	Landsat 8	0.855153		
17	GL087095E27829N	1988/05/30	Landsat 5	0.109268	0.0006	2.50
		1995/10/25	Landsat 5	0.110572		
		2008/10/12	Landsat 5	0.110385		
		2017/12/08	Landsat 8	0.111231		
		2023/06/08	Landsat 9	0.112007		

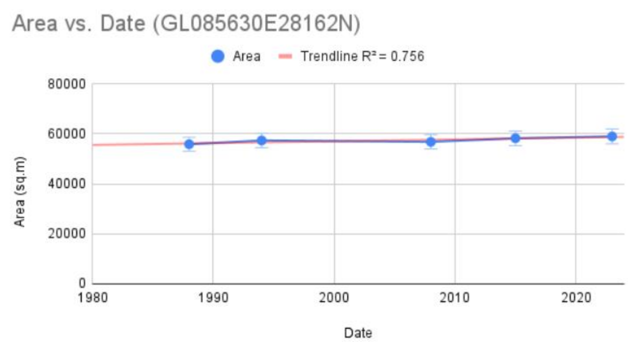
18	GL082673E29802N	1988/10/10	Landsat 5	0.024454	0.0109	179.9
		1998/10/06	Landsat 5	0.024253		
		2009/08/01	Landsat 5	0.037965		
		2016/09/05	Landsat 8	0.047671		
		2023/09/01	Landsat 9	0.068451		
19	GL087934E27790N	1989/10/25	Landast 4	0.114078	0.0007	2.45
		1996/11/05	Landsat 5	0.114572		
		2005/10/13	Landsat 5	0.115507		
		2015/10/09	Landsat 8	0.116292		
		2023/06/09	Landsat 8	0.116882		
20	GL087893E27694N	1988/10/14	Landsat 5	0.026116	0	-0.24
		1997/08/20	Landsat 5	0.032848		
		2009/09/22	Landast 5	0.032844		
		2015/10/09	Landsat 8	0.026438		
		2023/06/09	Landsat 8	0.026053		
21	GL087632E27729N	1988/10/14	Landsat 5	0.03117	0	-1.07
		1996/10/20	Landsat 5	0.030329		
		2005/10/13	Landsat 5	0.031681		
		2016/10/27	Landsat 8	0.032011		
		2023/01/23	Landsat 8	0.030836		

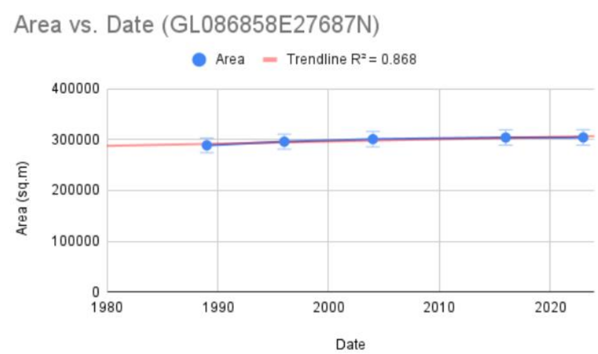
ANNEX B: Area Visualization with a chart view including a 5% error bar

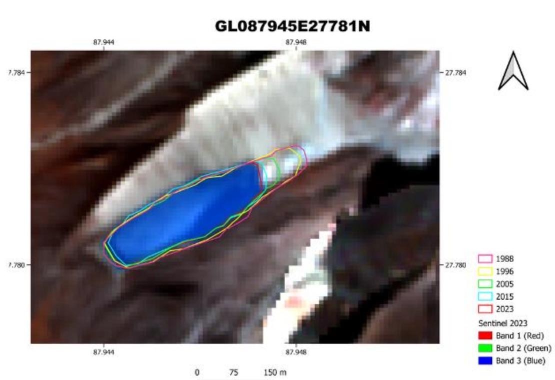


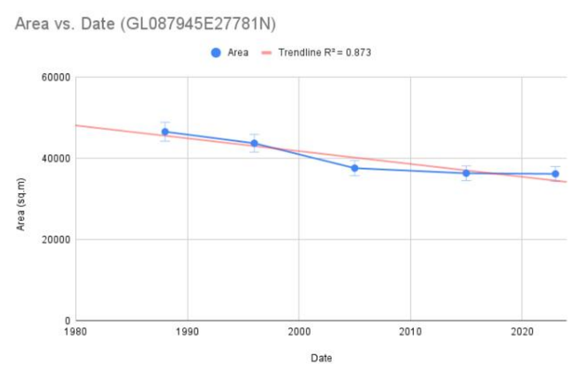




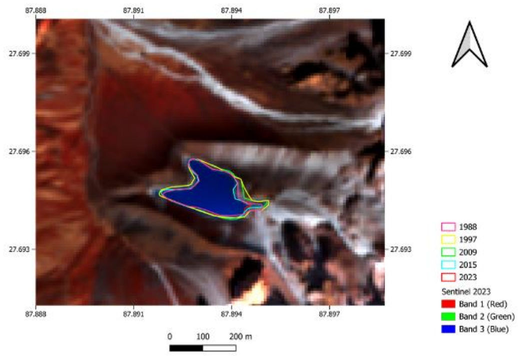


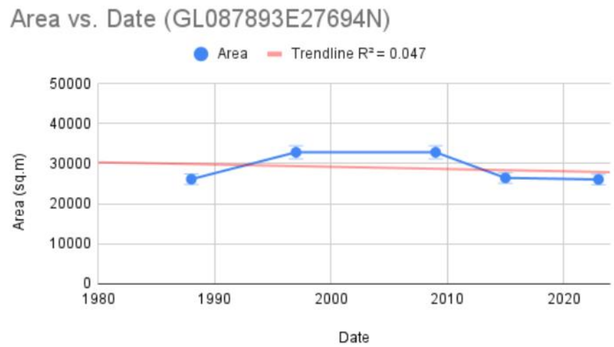




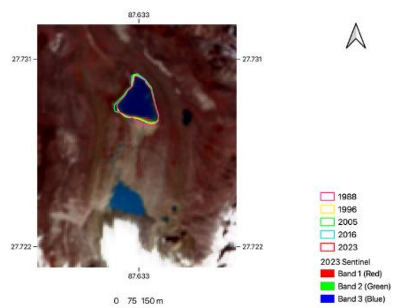


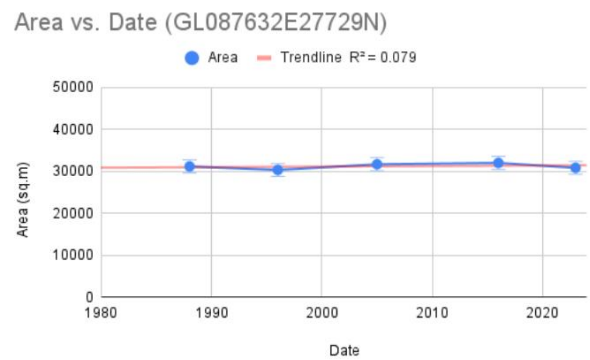
GL087893E27694N



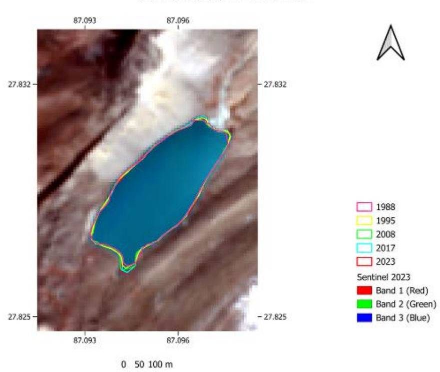


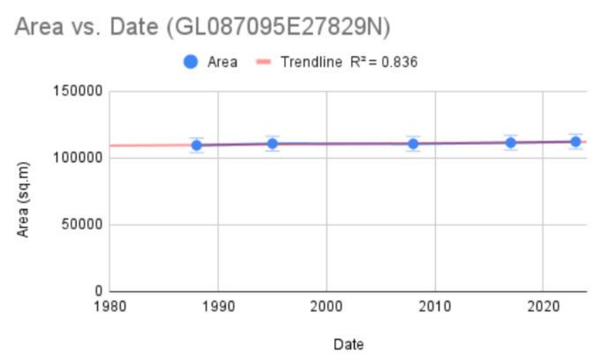
GL087632E27729N



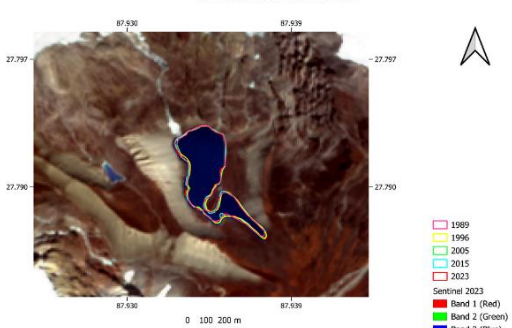


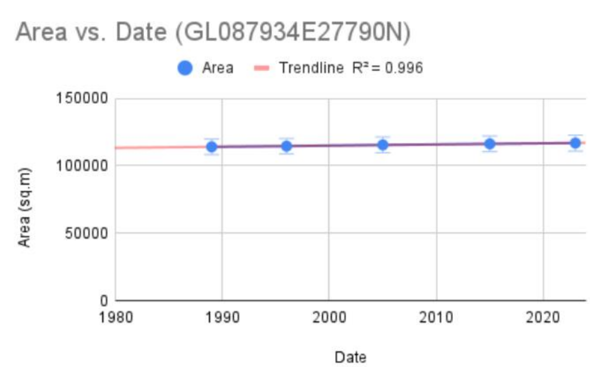
GL087095E27829N



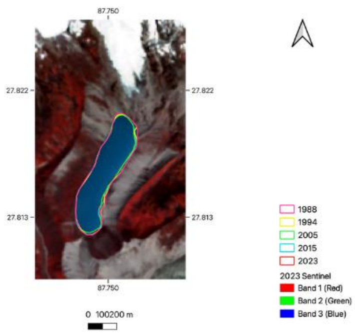


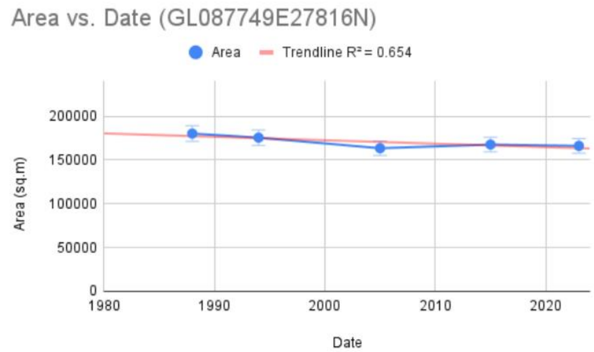
GL087934E27790N



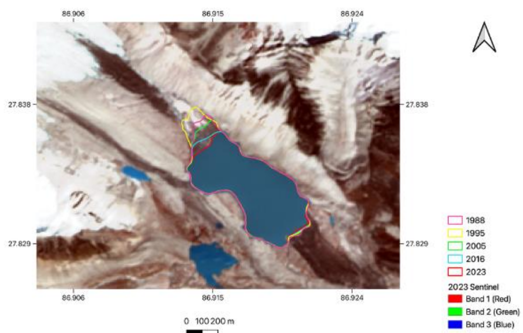


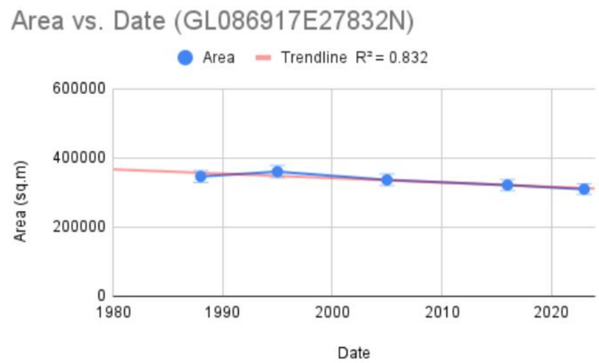
GL087749E27816N



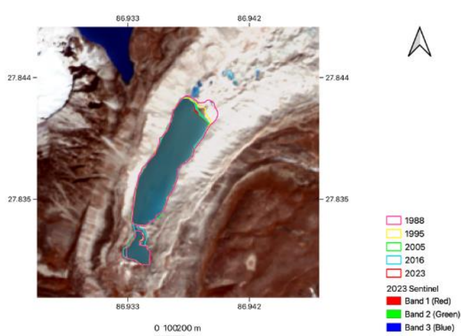


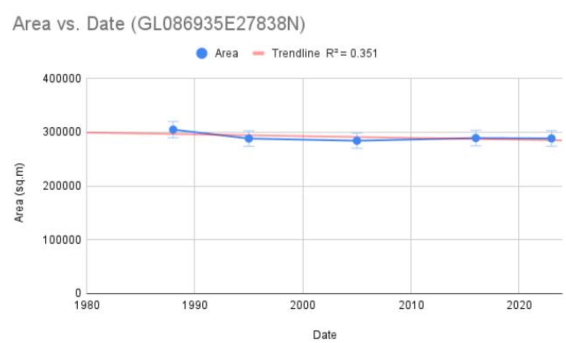
GL086917E27832N



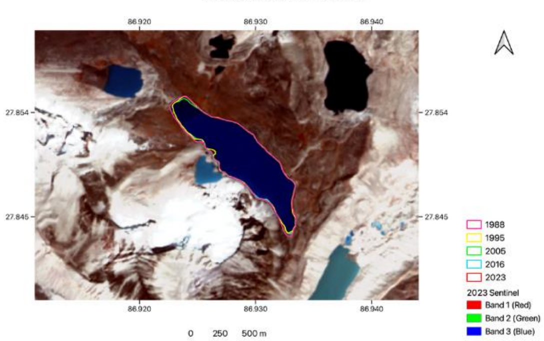


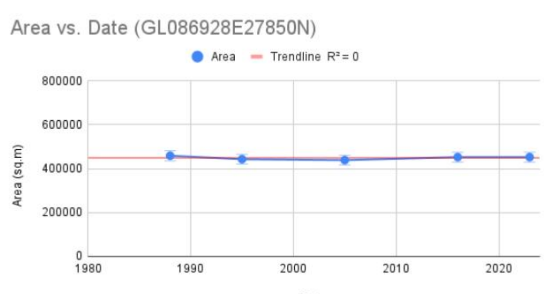
GL086935E27838N



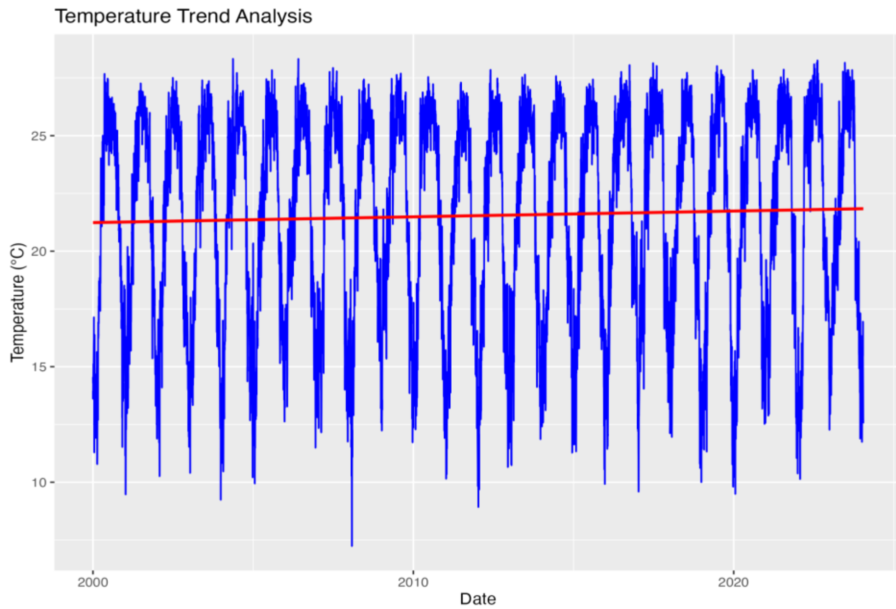


GL086928E27850N

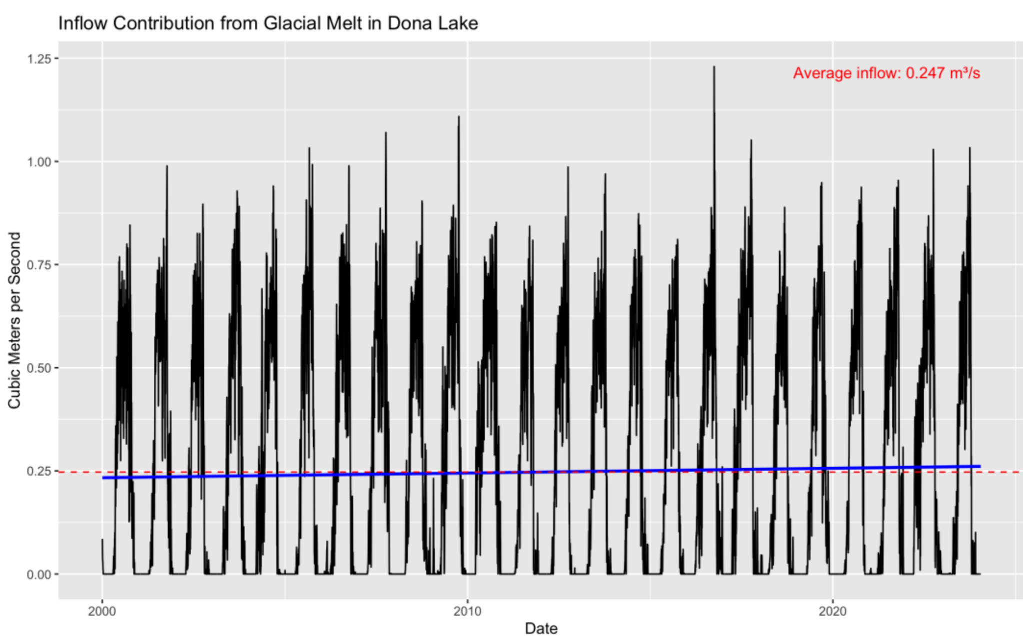




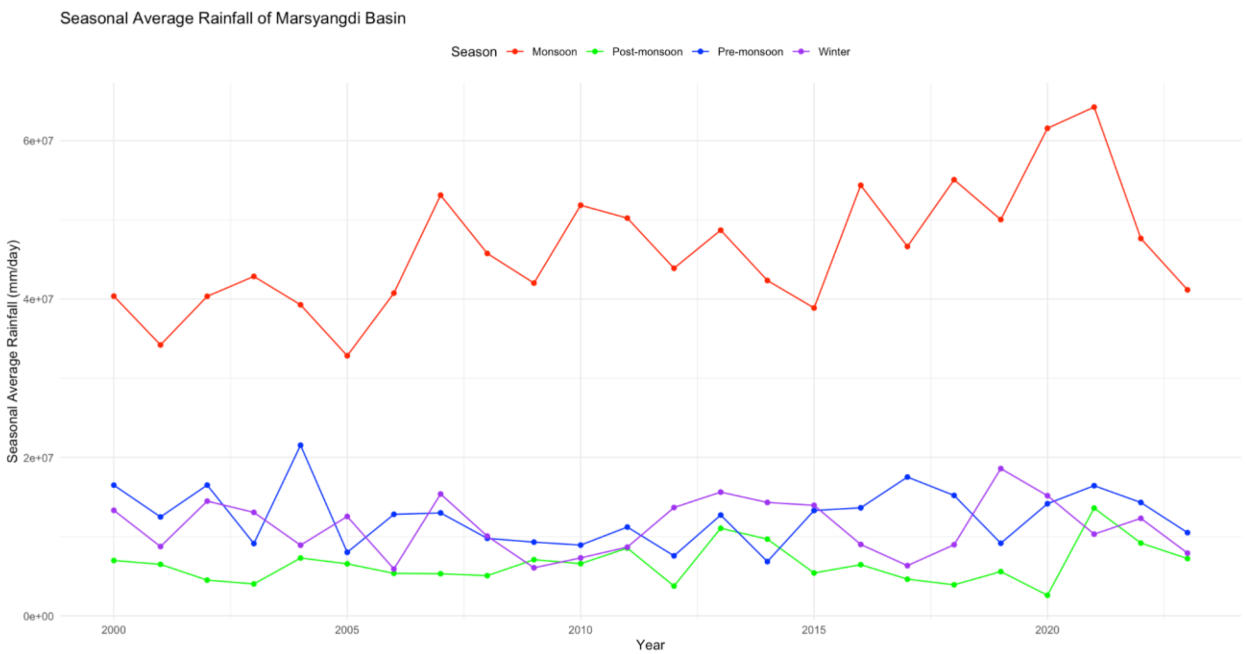
ANNEX C: Temperature Trend



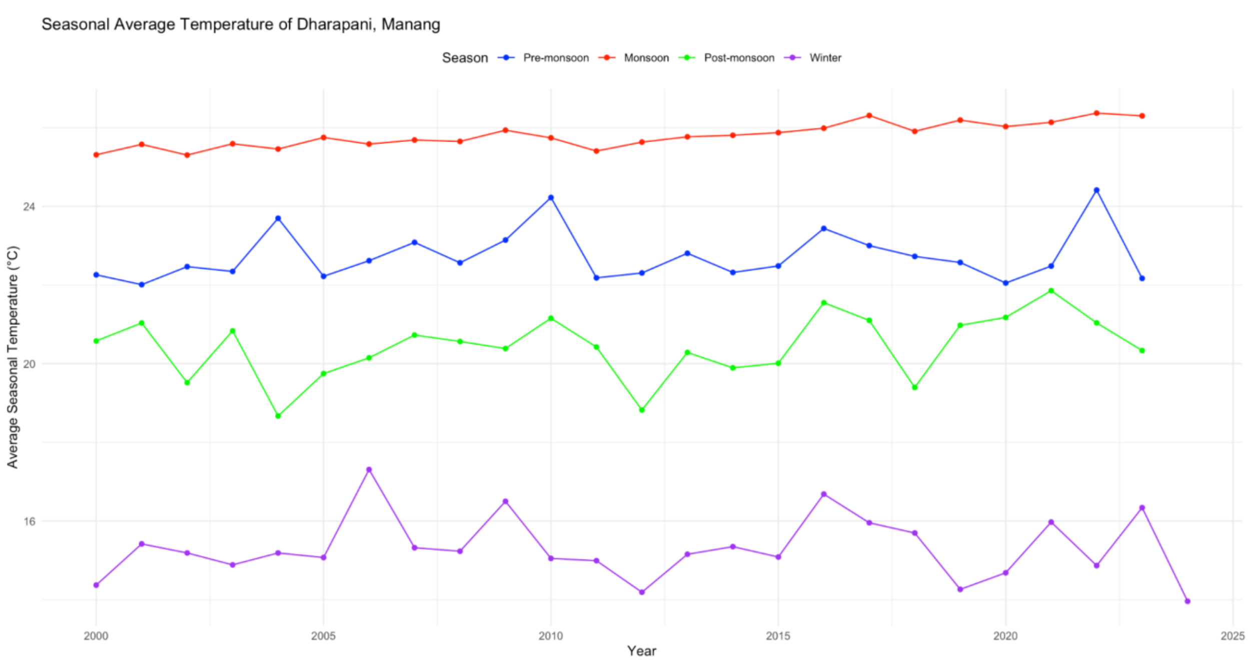
ANNEX D: Inflow Contribution from Glacial Melt in Dona Lake



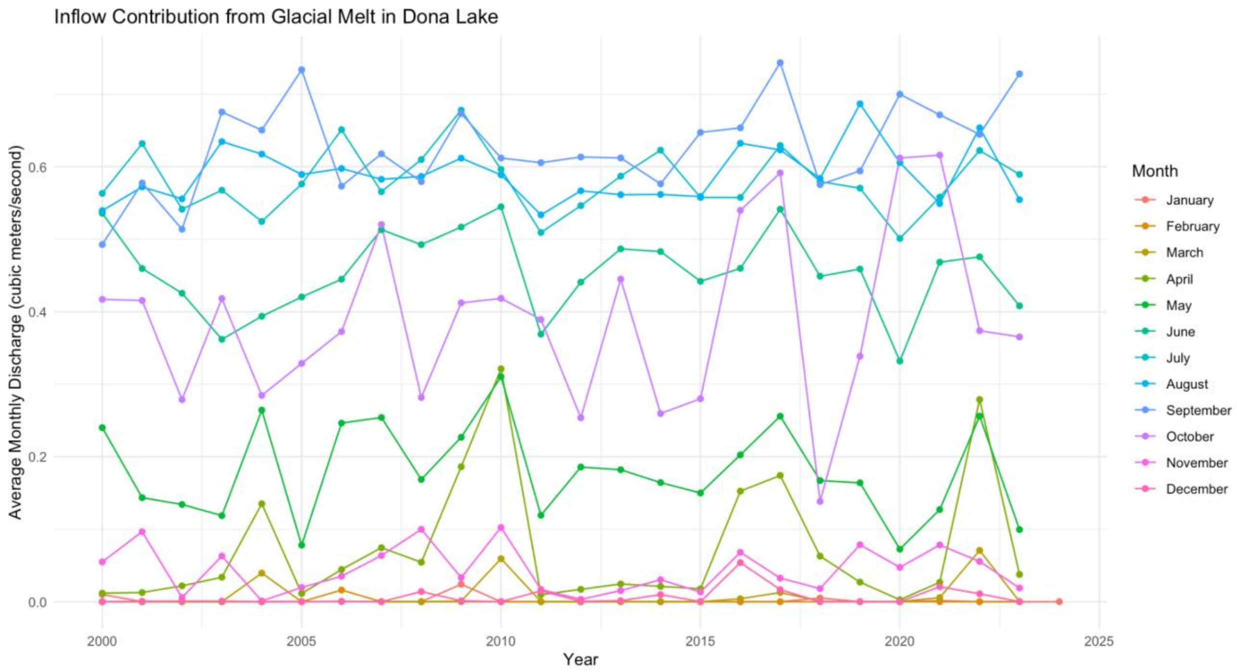
ANNEX E: Seasonal Average Rainfall



ANNEX F: Seasonal Average Temperature



ANNEX G: Monthly melt discharge to the Dona Lake



ANNEX H: Monthly Stats

Month	Qmonthlyavg	QmonthlyStdDev
1	0.00166730149170195	0.0130159232933427
2	0.000667687336119305	0.00605341382781262
3	0.00810372859418558	0.0387624879981344
4	0.0733414764981996	0.110428725384606
5	0.180460210231233	0.13789785724721
6	0.4551443671232	0.153737075959373
7	0.580697351186031	0.108760776179802
8	0.589480357209528	0.119049341146248
9	0.627729941325874	0.17019265142489

10	0.389619939142772	0.319735558087107
11	0.0438197894161523	0.0736372235579971
12	0.00611348488525488	0.0262584390583961

ANNEX I: Monthly Trends

Test_Series	P_value	Z_statistic	sens_slope	S	varS	tau	alt_hypothesis
Jan Discharge	0.414	-0.815	0	-27	1016.33	-0.137	TRUE
Feb Discharge	0.896	0.130	0	4	528.667	0.029	TRUE
Mar Discharge	0.052	1.942	2.156E-07	74	1412.67	0.307	TRUE
Apr Discharge	0.286	1.066	0.0008	44	1625.33	0.159	TRUE
May Discharge	0.441	-0.768	-0.0023	-32	1625.33	-0.115	TRUE
Jun Discharge	1	0	-1.601E-05	0	1625.33	0	TRUE
Jul Discharge	0.980	0.024	9.487E-05	2	1625.333	0.007	TRUE
Aug Discharge	0.747	0.322	0.0005	14	1625.33	0.050	TRUE
Sep Discharge	0.062	1.860	0.004	76	1625.33	0.275	TRUE

Oct Discharge	0.471	0.719	0.002	30	1625.33	0.108	TRUE
Nov Discharge	0.823	0.223	0.0002	10	1625.33	0.036	TRUE
Dec Discharge	0.270	1.101	9.0459E-06	45	1597	0.167	TRUE