ANALYTICAL HIERARCHICAL MODELING OF GLACIAL LAKE OUTBURST FLOOD POTENTIAL IN THE KHUMBU REGION, NEPAL

A Thesis
by
Alex O'Neill

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Abstract

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The Himalayas have seen increasingly devastating glacial lake outburst floods (GLOF), particularly in recent years. These floods are becoming more significant and common as the climate continues to rapidly warm in the region, making accurate and frequent accounting of GLOF hazards a top priority. This study presents a methodology for efficiently modeling GLOF hazards using predominately free, global satellite remote sensing data in conjunction with an analytical hierarchical model (AHP) to inventory GLOF hazards in the Khumbu Region. Findings indicate rapidly retreating and thinning glaciers with a 34% increase in lake area, including a 303% increase in supraglacial water area. Using Imja Tsho to evaluate the sensitivity of the model, 25 potentially hazardous lakes are delineated, with four classified as very high risk and four classified as an extreme risk. Imja Tsho and Lumding Tsho rank as the highest-risk glacial lakes, with Lumding Tsho increasing its growth rate 77% percent in 2013-2019 versus 1962-2007. Unlike Imja Tsho, no mitigation work is in place to reduce the risk posed by Lumding Tsho, and few in situ studies have been conducted.

Based on these findings, it is critical to form a mitigation plan to lower the risk associated with Lumding Tsho and assess the potential impact of an outburst event. Projected warming of the region and associated increase in GLOF hazard shows the continued study of GLOF hazards and mitigation is crucial to protecting vulnerable communities.

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I gratefully acknowledge the efforts and dedication of my parents, Bill and Paula, as well as my grandparents, who fostered my curiosity and never stopped encouraging me to pursue my dreams, no matter the obstacles. I am especially grateful to the teachers at the Trilogy School in Raleigh, NC, who saw in me potential and allowing me to build the foundational knowledge that brought me here, all these years later. I owe a great debt of gratitude to my wonderful, supportive partner, Jessica McClelland, who has helped me though countless sleepless nights and panicked ramblings. Lastly, I am grateful to the many occupants of Rankin Science West, who have put up with me wandering the halls at all hours of the day with my dog, who spent the better part of a year with me in the office.

Table of Contents

List of Tables

List of Figures

Foreword

The main body of this text is formatted for submission to the Mountain Research section of Mountain Research and Development, a journal of the International Mountain Society. It is formatted in accordance with the style guide provided to authors by Mountain Research and Development.

Introduction

Although Glacial Lake Outburst Floods (GLOF) have always been a fact of life in the Himalaya, rapid changes in the climate of the mountain range have set the stage for larger and more frequent GLOF events. As overall temperature and freezing level heights continue to rise, accelerated glacial retreat is causing the rapid expansion of previous stable glacial lakes, as well as the formation of previously non-existent lakes. The increasing retreat of these glaciers have culminated on the creation of more than 5,000 glacial lakes, many of which are potentially dangerous to downstream communities. The rapid lake growth in the Himalaya significantly outstrips that of neighboring mountain ranges (Veh et al. 2020).

The Himalaya are disproportionately impacted by anthropogenic climate change, with the trend of rapid warming and unstable precipitation regimes projected to continue into the coming decades (Rajbhandari et al. 2016; Perry et al. 2020). This indicates that the retreat of large glaciers, and the associated expansion of hazardous glacial lakes, will continue to accelerate. Based on these trends, the efficient and repeatable inventorying of glacial lake hazards will only become more important in the near future. The traditional method of assessing a glacial lake for GLOF potential involves a field campaign to take in-situ measurements of the moraine dam, as well as conduct a bathymetric and topographic survey. While this approach yields data that are not possible through remote sensing, it is both time and resource intensive. With the increasing frequency of GLOF events, a more efficient method is required identify hazardous glacial lakes before they experience an outburst event.

The purpose of this study, conducted in its entirety by the author, is to advance the understanding of modeling GLOF risk in remote mountain areas, where data are limited, and fieldwork is difficult or impossible. The methodology leverages predominantly remotely sensed and model-based datasets available globally to achieve this goal. While the methodology used in this study does not replace a full-fledged, in-situ survey of a glacial lake, it acts as a filter to identify the most hazardous lakes rapidly and accurately, which can then be prioritized for closer study and mitigation work. Additionally, this study aims to quantify the pace of glacial lake expansion in the region, as well as determine the adequacy of current mitigation strategies in place.

Multi-Criteria-Decision-Analysis (MCDA) has become the one of the most widely accepted ways of weighting factors in complex GIS-based decision models (Jiang and Eastman 2000). Among the numerous MCDA models developed, the Analytical Hierarchical Processing model, AHP, is one of the most flexible and popular when dealing with complex problems (Saaty 1987). Due to its ability to handle complex environments by quantifying the predictive force of qualitative factors, AHP modeling has become the cutting edge method when modeling natural hazard susceptibility and environmental phenomenon (Abella & Van Westen 2007; Kayastha et al. 2013; Nefeslioglu et al. 2013; Paudel & Andersen 2013; Kumar et al. 2017; Andersen & Sugg 2019). This study uses model weights from a similar study conducted in the Western Himalaya, and was evaluated using Imja Tsho as a sensitivity metric, a lake in the study area that is well documented as an extreme hazard. The accuracy of the model in multiple regions points to the robust nature of AHP modeling.

Findings indicate that between 2000 and 2019, glacial lake area increased by more than 30%, while the area of supraglacial lakes increased by over 300%. This indicates that in addition to retreating laterally, the region's glaciers are thinning rapidly. The AHP model found that in addition to Imja Tsho, three lakes present an extreme risk. Among these, Lumding Tsho has the same hazard level as Imja Tsho. Lumding Tsho is particularly alarming, as it has had little in-situ study conducted, and unlike Imja Tsho, no mitigation plan is in place. These findings provide justification for more intensive fieldwork and mitigation planning in the region.

Analytical Hierarchical Modeling of Glacial Lake Outburst Flood Potential in the Khumbu Region, Nepal

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Abstract

The Himalayas have seen increasingly devastating glacial lake outburst floods (GLOF), particularly in recent years. These floods are becoming more significant and common as the climate continues to rapidly warm in the region, making accurate and frequent accounting of GLOF hazards a top priority. This study presents a methodology for efficiently modeling GLOF hazards using predominately free, global satellite remote sensing data in conjunction with an analytical hierarchical model (AHP) to inventory GLOF hazards in the Khumbu Region. Findings indicate rapidly retreating and thinning glaciers with a 34% increase in lake area, including a 303% increase in supraglacial water area. Using Imja Tsho to evaluate the sensitivity of the model, 25 potentially hazardous lakes are delineated, with four classified as very high risk and four classified as an extreme risk. Imja Tsho and Lumding Tsho rank as the highest-risk glacial lakes, with Lumding Tsho increasing its growth rate 77% percent in 2013-2019 versus 1962-2007. Unlike Imja Tsho, no mitigation work is in place to reduce the risk posed by Lumding Tsho, and few in situ studies have been conducted. Based on these findings, it is critical to form a mitigation plan to lower the risk associated with Lumding Tsho and assess the potential impact of an outburst event. Projected warming of the region and associated increase in GLOF hazard shows the continued study of GLOF hazards and mitigation is crucial to protecting vulnerable communities.

1. Overview

The Himalayan Mountains are on the frontlines of climate change as one of the most environmentally sensitive regions of the planet (Immerzeel et al. 2020). As the climate becomes less stable, increasing mountain hazards such as landslides, avalanches, and glacial outburst floods threaten the existence of entire mountain communities and their populations (Xu et al. 2009). The early warning of these events stands a chance to save thousands of lives (Pokhrel et al. 2009). These hazards have historically been hard to predict due to the remoteness of the study sites and the lack of dense infrastructure.

While the above-mentioned mountain hazards are consequential, the hydrological hazards stand out as the most powerful and dynamic. With the observed intensification of the hydrologic cycle (Donat et al. 2016), flash flooding and glacial outburst floods (GLOFs) are an increasingly relevant and challenging to predict hazard (Huntington 2006). In addition to the potential increase in vulnerability to mountain hazards faced by Himalayan communities, the increase in temperature and subsequent loss of ice on high alpine routes has made said routes less stable in recent years. The ice previously acted as a binding agent for the many unconsolidated stone ridgelines and summit structures. The degradation of alpine ice will lead to increased rockfall on the lower slopes, which will make the climbing more treacherous.

With the continued rapid retreat and thinning of glaciers in the Khumbu region, there is a potential for more extensive and frequent glacial outburst floods in the 21st century as temperatures continue to rise (Bajracharya and Mool 2009; Mayewski et al. 2020; Miner et al. 2020). Indicated by the IPCC AR5 and the CMIP5 model set, the trends currently seen in Nepal's Khumbu region are likely to continue and even accelerate in the coming decades

(Rajbhandari et al. 2016). If these trends continue as projected, the threat posed to communities in the region will only increase as the size and amount of moraine-dammed and supraglacial lakes increase. The same glacial retreat responsible for the elevated GLOF risk is also responsible for the increased threat of flash flood events due to higher runoff and shorter lag periods associated with thinning glaciers and intense precipitation (Jansson et al. 2003).

Much of the research into mountain hazards has historically emphasized the 'muddy boots' approach to research. While in-situ research can provide valuable context to one's research, it can also be a limiting factor within this study area (Fig. 1)(Marston 2004 Oct 14). Given the high elevations, the ruggedness of the terrain, and the lack of dense infrastructure, it is simply not practical or feasible, from both a physical and logistical perspective, to cover the entire region in a detailed ground survey with any frequency.

Field-based research methods were pioneered in the latter third of the 20th century. These early studies found that the Everest region was a fairly stable (Byers 1986) so this lack of a temporal resolution was not considered a significant limitation. With the rapid pace of change in this part of the world today, year to year conditions can quickly nullify the data collected even a short time ago. These changes are also hard to model on a large scale, as the processes vary greatly from location to location (Hewitt and Liu 2010; Song et al. 2017). A recent article and photo essay by a French mountain guide illustrated just how rapid the pace of change has become in the world's high alpine areas (Bertorello 2019).

This study employs a methodology to efficiently and accurately assess the current status of GLOF hazard using free, global extent data using and AHP model. Additionally, this study assesses trends in glacial lake expansion from the year 2000 through 2019, a key marker in future GLOF hazard (Veh et al. 2020). Following the analysis of GLOF hazards, this study explores the mitigation strategies in place to avoid catastrophic outbursts, and asses if they are adequate.

2. Literature Synthesis

Water Towers of Asia

Known as the 'Third Pole', the Himalaya and greater Tibetan Plateau form the third-largest freshwater source in the world, behind water held in Antarctica and Arctic ice (ICIMOD 2019). The meltwater from this region forms the headwaters of ten of Asia's largest river systems, with an immediate impact on 1.3 billion people living in these basins, and a direct effect on the food and water supply of over 3 billion individuals, or nearly half the world's population (Bandyopadhyay 2013; Paudel & Andersen 2013; Immerzeel et al. 2020). While this extreme reliance on so-called 'water tower mountains' is highly prevalent in Southern Asia, it is not unique. La Paz, Bolivia, is a prime case study, as much as 30% of its water budget is composed of meltwater (Soruco et al. 2015.).

Intensification of the Hydrologic Cycle

The increased frequency and intensity of extreme heavy precipitation events (>95th percentile) have risen in the past several decades, while annual precipitation has remained steady (Perry et al. 2020). These data indicate more substantial monsoonal precipitation with more dry and low precipitation days or an overall intensification of the hydrologic cycle (Huntington 2006). From controlling water supply to erosion, it is one of the primary drivers of an environment. An environment adapts over time to cope with trends in precipitation totals, but reacts slowly to extreme events. This can often lead to significant flooding, especially in historically dry regions with low infiltration rates. Donat et al. (2016) use a combination of observational data and numerical models at both the local and regional scale to test the validity of whether extreme precipitation events are becoming more intense and whether precipitation totals are increasing. This study found that while the number of extreme precipitation events and total precipitation is trending upward globally, areas which are the driest have seen a disproportionate increase. Through the analysis of historical weather station data, these same trends have also been observed across the Himalaya in central Nepal (Karki et al. 2017), additionally, the CMIP5 climate mode indicates that these patterns will only intensify over the next 50 years (Rajbhandari et al. 2016).

For this study's purposes, the intensification of the hydrologic cycle impacts all four hazards mentioned below; 1) avalanches, 2) rockfalls, 3) landslides, 4) glacial outburst floods. Research has shown that the most dangerous form of avalanche, large slab avalanches, are often preceded by a dry spell followed by heavy precipitation (Hardy et al. 2001; Ballesteros-Cánovas et al. 2018), the very pattern which the Himalaya are trending towards (Karki et al. 2017). The extreme precipitation events caused by this intensification are also significant drivers of landslides and glacier lake outburst floods. The excess water and flooding caused by these events, in conjunction with a rising freezing levels, are a major trigger of the catastrophic events. Therefore, the ability to predict the long dry spells followed by extreme precipitation patterns could prove extremely valuable in predicting such mountain hazard events (Pokhrel et al. 2009).

Multi-Criteria-Decision-Analysis and Analytical Hierarchical Processing

The use of Multi-Criteria-Decision-Analysis (MCDA) has become the one of the most widely accepted ways of weighting factors in complex GIS-based decision models (Jiang and Eastman 2000). Among the numerous MCDA models developed, the Analytical Hierarchical Processing model, AHP, is one of the most flexible and popular when dealing with complex problems (Saaty 1987). Due to its ability to handle complex decision making problems as well as to quantify the predictive force of qualitative factors, the AHP model has become the cutting edge, yet well established, method when modeling natural hazard susceptibility and environmental phenomenon (Abella and Van Westen 2007; Kayastha et al. 2013; Nefeslioglu et al. 2013; Paudel and Andersen 2013; Kumar et al. 2017; Andersen and Sugg 2019).

The two main ways in which variables are factored in an AHP model are through 1) expert ranking and 2) statistical weighting based on case events. Expert ranking involves surveying individuals to determine variable weights used in the model. Using the statistical method, case events are used to create a pairwise comparison matrix (Saaty 1987). The factors are assigned values within the comparison matrix, 1-9, with 1 indicating that both factors in the pair are of equal importance, and with 9 indicating the factor is extremely important and of very high predictive value in comparison to its paired factor (Kumar et al. 2017; Andersen and Sugg 2019). The validity and robustness of the pairwise comparison values are determined using the eigenvalues associated with the given pairs. The model weights used in this study are borrowed from a similar study done in a neighboring region of the Himalaya, and are based on statistical weighting (Prakash and Nagarajan 2017).

Mass Movement:

Looking at the historical record of 41 GLOF events from the regions surrounding the study area, more than half of them can be directly attributed to mass wasting leading to an overtopping of the moraine damn (Prakash and Nagarajan 2017). This stresses the importance of considering these mass wasting events as significant drivers of GLOFs. Therefore, they must be taken into account when assessing the risk of a catastrophic outburst.

Given that landslides, rockfalls, and avalanches, are influenced by similar processes, much of the factors involved in predicting them are the same. Although land- and mud-slides have always been objective hazards in Nepal, there has been a significant upward trend in fatal landslides in recent years (Petley 2017). This upward trend has been linked to changes in the monsoonal precipitation patterns (Petley et al. 2007; Gariano and Guzzetti 2016). Avalanches, likewise, are heavily driven by both slope and precipitation patterns. While snow-covered slopes with angles between 30º and 60º (Rounce et al. 2016) are a well-documented predictor of avalanches, a second, harder-to-observe driver is present. Near-surface faceted crystal formations in the snowpack have a significant influence over the occurrence of a slab avalanche (Hardy et al. 2001). Faceted crystals form most frequently during an extended dry period with intense insolation. Therefore the marked intensification of the hydrologic cycle in Nepal would indicate that there will be an increase in severe avalanches in the coming years (Karki et al. 2017).

Unlike landslides and avalanches, rockfalls are not as heavily influenced by precipitation. Rockfalls occur on steep slopes and rock faces when a large section of the face, or boulders, give way and break off, collapsing down the face with incredible power and destructive force. These events are often not predictable and happen over a very short time-frame. Throughout the world, rockfalls in glacierized areas have become increasingly common, primarily credited to the melting of ice and permafrost which previously acted as a bond to hold the structure together (Rambourg 2019). Additionally, the rapid retreat of glaciers in combination with the melting of permafrost has led to increased buttressing events, or the large release of rock from steep and sheer faces (Dorren 2003; Deline et al. 2014; Alberti and Spreafico 2019)

<u>Glacial Outburst Floods:</u>

Glacial outburst floods are among the most serious of natural hazards in the Himalayas (Kattelmann 2003). They hold the potential for the destruction of communities with little warning. They are hard, if not impossible, to predict, given the sudden onset of events combined with the long, non-regular periodicity of the events (Nie et al. 2018). While the forecasting of these events remains unreliable, much headway has been made to identify and inventory potential glacial lake outburst floods through remote sensing and GIS modeling. This progress led to the successful creation of a GLOF vulnerability index map in 2007 (Kattelmann 2003; Bajracharya et al. 2007; Bolch et al. 2008; Westoby et al. 2014; Somos-Valenzuela et al. 2015a; Falátková 2016). With the continued rapid retreat and thinning of glaciers in the Khumbu region, there is the potential for more significant and frequent glacial outburst floods in the 21st century as temperatures continue to rise (Bajracharya and Mool 2009). This was largely confirmed in a study linking the expansion of ice- dammed glacial lakes to the thinning of glaciers in the Everest region of Nepal (Song et al. 2017).

The two major failure mechanisms of glacial lakes break down into two categories; self-destruction of the dam and overtopping waves created by mass movement into the lake. Glacial lakes are vulnerable to multiple forms of mass wasting, including those most impacted by climate change, being rockfall and ice avalanches (Deline et al. 2014; Byers et al. 2019; Alberti and Spreafico 2019; Rambourg 2019). The second major cause of glacial lake outburst is dam self-destruction, or the loss of integrity due to piping, or the melting of an ice core. One of the best indicators of this potential is through the analysis of distal slope angle. Overly steep slopes seen on the moraine dams in many Himalayan lakes indicate low stability in the face of the rising hydrostatic pressure of expanding lakes (Fujita et al. 2013).

While this study focuses on larger, moraine dammed lakes to prioritize the highest risk glacial lakes, an accounting of all glacial lakes and ponds is conducted to create an overall inventory of lakes. This is important, as even the smaller, supraglacial ponds can experience damaging GLOF (Rounce et al. 2017). The hazard potential of supraglacial lakes was not modeled, as englacial transport and failure can not be accurately modeled through remote sensing.

3. Data & Methods

To successfully inventory and assess the glacial lakes of the Khumbu, four classes of data, Table 1, are collected and analyzed: 1) the new Nepal weather stations installed by a recent expedition (Matthews et al. 2020); 2) recently released ERA5 climate reanalysis dataset for the same region (Copernicous 2017); 3) Landsat imagery; and 4) Digital Elevation Models (DEMs). The DEM dataset consists of four models of various extents and spatial resolutions, resampled and clipped to the study area extent to overcome the voids common in elevation models of the Himalaya. Note the High Mountain Asia DEM accounted for the majority of the data, including the entirety of moraine dams of each lake studied. The study area, the Sagarmatha political zone (Fig. 1), is used due to the location of the weather stations and the importance of this region to the tourism economy of Nepal (Nepal 2005; Baral et al. 2017).

The region of interest is the Sagarmatha Zone of Nepal, following its western border and cutting northeast along ridgelines from Lukla to Lhotse in the east. This area forms the Dudh Kosi's upper watershed, a major tributary to the Sun Kosi River, which supplies water to hundreds of millions of people. The region has elevations ranging from 2,200 meters above sea level to over 8,000 meters, resulting in a tremendous amount of potential energy stored in its peaks (Zimmermann et al. 1986).

Using the Landsat 7 and 8 imagery collected in 2000 and 2019, respectively, a series of classifications and water segmentations in ArcGis Pro 2.5 (ESRI 2020) using visual interpretation digitization methods is conducted to determine the location of and total area of supra glacier lakes (Pacirici et al. 2007; Stokes et al. 2007). This study uses the most modern, high-quality sensor available for a given year. Landsat imagery pulled from September-January, using a cloud cover threshold of 10%

For each given time period, a Modified Normalized Difference Water Index (MNDWI) (Xu 2005) is calculated, and with the slope layer, a classification in ArcPro's Raster Calculator (ESRI 2020) tool is used to create a rough mask of water bodies, Figure 2. The glacial lakes are manually delineated using the MNDWI classification as a reference and a shapefile with the locations and areas digitized. The visual interpretation process also takes advantage of Normalized Difference Water Index (NDWI), Color Infrared (CIR) and true color band combinations to determine the most accurate extent of a given lake.

Given the lack of in-situ bathymetric data for these remote lakes, lake volumes are not available in a widespread dataset. To approximate the volume of the glacial lakes, a Markov Chain Monte Carlo simulation is run through R using the JAGS language (Plummer 2018) trained using a database of 24 bathymetric surveys of glacial lakes in the Himalaya. Using this simulation, 100,000 lake depths are calculated for each of the 500 lake areas (Veh et al. 2020). This dataset is then used to create a linear model with which the depth of the glacial lakes can be approximated, equation 1. The glacial lakes are assumed, for this study, to be circular with an ellipsoidal bathymetry. While this is likely not the case with every lake, it roughly approximates the volume of the glacial lakes. While the total volume of glacial lakes is not used in the AHP modeling, it provides additional context to the growth of glacial lakes in the region.

Other factors extracted from the data are the distance between the glacial snout and the lake, slope of said distance, freeboard height, and dam height to width ratios, crest width and distal slope (slope of the dam face). A lake's susceptibility to impact by a mass-wasting event is assessed using the slope and landcover of the adjacent terrain. Slopes of greater than 30^{o} are considered moderate risk, with slopes over 55^{o} considered very high risk to rockfall and avalanche (Hardy et al. 2001; Jaboyedoff and Labiouse 2011; Kumar et al. 2017). Additionally, Google Earth imagery are analyzed for signs of previous mass wasting events (i.e. debris cones) as well as hanging glaciers and seracs, as these are both indicative of high risk. The presence of either on a slope greater than 30^{o} was noted as high riskin the model inputs.

The glacial lake and dam's geometric features are extracted from the DEM layer using ArcPro's Stack Profile tool (ESRI 2020). This tool enables the user to extract surface elevation profile from the DEM layer along the path of a line, as shown in Figure 3. In the use of this study, the only glacial lakes with an area greater than .1 km^2 were included, as these lakes are considered the highest risk (Iribarren-Anacona et al. 2014). Seismic activity in the region has historically been stable, with four events greater than Magnitude six in the past 100 years (Wald 2016; Miner et al. 2020). Likewise, cloudburst potential in the region is sporadic, but with trends of extreme precipitation events on the rise in recent years (Paudel and Andersen 2013; Karki et al. 2017; Bohlinger and Sorteberg 2018)

These factors are then converted into model input values in accordance with the Prakash & Nagarajan (2017) study, Table 2. This study conducted a remote assessment of GLOF hazard in the western Himalaya. The values are input into the model equation using the weight ranking from the 2017 study, equation 2. Previous analysis of GLOF events shows that, using this AHP model, the risk of an outburst occurring is very high at values above 0.65 (Prakash and Nagarajan 2017). Using this as a guide, the lakes were classified into four groups; moderate (<0.45), high (0.45 – 0.55), very high (0.65 – 0.75), and extreme probability (>0.75) of an event.

Imja Tsho, a moraine-dammed glacial lake, is known to be at significant risk of an outburst flood event, with active monitoring and mitigation programs (Westoby et al. 2014; Somos-Valenzuela et al. 2015b; Rounce et al. 2016; Aggarwal et al. 2017; Song et al. 2017; Veh et al. 2020). The most significant mitigation program is the addition of a drainage canal in the dam structure of the lake, which lowered the water level and acts as a series of retaining ponds. This system is somewhat effective; however, a large overtopping wave has the potential to destroy these earthworks and lead to a GLOF (Mckinney et al. 2018). Imja Tsho is used as a sensitivity analysis metric for the AHP model, given its status as a known extreme risk.

4. Results

Glacial Lake Expansion

The main result of this section of the study was the dramatic growth seen in the area and volume of glacial lakes. Between the years 2000 and 2019, the Khumbu region saw an estimated 34% increase in glacial lake area, with an estimated 42% increase in the total volume of water present in liquid form. Volume estimates are not produced for supraglacial lakes, as the lack of bathymetric data and high variability of supraglacial lakes renders estimates unreliable.

When looking closer at the data, a trend of rapid expansion is almost one order of magnitude larger for supraglacial lakes, with an estimated 303+ increase in supraglacial lake area between 2000 and 2019. This trend varies slightly from glacier to glacier, with the highest rates of lake expansion seen on the Ngojumpa, Lunak, Khumbu and Lhotse glaciers in the north and central regions of the study area, seeing a 361%, 279%, 266% and 509% increase in area, respectively. Figure 5 illustrates this expansion near the tongue of the Ngojumpa glacier. Image A1 and B1 are CIR images derived from 2000 and 2019 Landsat imagery, respectively. Images A2 and B2 are MNDWI images derived from the same imagery. A2 and B2 show the rapid growth in surface water, shown as bright green.

GLOF Hazard Model

Table 3 shows the results of the data extraction and AHP modeling. As illustrated in the above section, Table 3 indicates high growth rates among many of the largest lakes in the region. Mass movement potential is ranked as the highest value predictor in the model and is very high among the glacial lake surveyed, with an average model input value of 0.68 out of 1—this, combined with very little freeboard height at many of the lakes, is highly concerning. All but three of the lake reside below 5400msl, which puts them below the monsoonal freezing level, and points to a large amount of ablation and liquid precipitation.

Within the model classification schema, seven lakes fell under the moderate grouping, six under the high grouping, four under the very high grouping, and four under the extreme grouping, Figure 6. Notably, Imja Tsho showed the highest probability with an AHP score of .8125. A second lake, Lumding Tsho, scored a nearly identical .81, Table 3. With many of the factors that make up the model highly influenced by anthropogenic climate change, these values will likely increase significantly in the coming years.

5. Discussion

Supraglacial Lake Expansion

The rapid expansion of supraglacial lakes seen in this study is evidence that freezing level heights in the region are rising and causing a thinning of the region's glaciers. With freezing level heights predicted to continue rising, especially during the monsoonal accumulation season (Perry et al. 2020), a more intense and prolonged ablation season will continue to increase the glacial retreat rate and lead to the formation of new, hazardous glacial lakes. This process is underway at the tongue of the Ngojumpa Glacier, where the supraglacial lakes have expanded dramatically since 2000 and are beginning to coalesce into one larger, terminal lake, Figure 4. This lake expansion is directly related to increasing hazard levels (Iribarren-Anacona et al. 2014). With the recent observations indicating that the ablation season in the Khumbu region is growing to encompass more of the year, these processes are likely to accelerate (Pelto 2021).

Lumding Tsho

While Imja Tsho is well studied and has mitigation practices in the form of a drainage canal in place, the same cannot be said for Lumding Tsho (Khadka et al. 2019). This is striking, as it holds a hazard score essentially the same as Imja Tsho. Several surveys have been done of Lumding Tsho (Pelto 2012; Rounce et al. 2016), however they have not been a holistic assessment of its risk with mitigation proposals. The lake's rapid and accelerating growth rate indicates that Lumding Tsho will only become a greater risk in the coming years. Lumding Tsho, a terminal lake in the study area's western region, has significantly increased its expansion rate. From 1962-2007, the caving face of Lumding Glacier retreated at an average of 40 m yr^{-1} (Pelto 2012). This study finds that from 2013-2019, the caving face of Lumding Glacier retreated an average of 71 m yr^{-1}, or an increase of 77%, Figure 6. This increased rate coincides with the timing of the increase in freezing level height climb seen in the region over the past two decades (Perry et al. 2020).

In addition to the lake area's rapid expansion, the surrounding topography of Lumding Tsho only increases the risk level with the potential of large mass wasting events. The former tributaries to Lumding Glacier have retreated up the valley wall to become hanging glaciers with slopes of 20º to >50º. This is significant, as it puts the calving face of multiple hanging glaciers directly above the lake surface. In addition to the inherent instability of seracs and hanging glaciers, the calving faces of the glaciers above Lumding Tsho are at ~5300 msl, below the monsoonal freezing level. This indicates that a mass- wasting event from one of the several hanging glaciers is likely as they are subjected to increased temperature and liquid precipitation, and a lengthened ablation season. More hanging glaciers up the valley from Lumding Tsho will likely increase the risk of mass movement into the lake in the coming years. Large amounts of debris surrounding the lake as well as the glacier indicate frequent rockfall events. A 2016 field survey of Lumding Tsho (Rounce et al. 2016) largely corroborates these risks.

In the event of a mass movement into the lake, even a small wave would be problematic, as the Lumding Tsho has a surface drainage channel in its moraine dam. Unlike that of Imja Tsho, this is not a constructed channel but rather an erosional channel. The presence of surface drainage indicates no freeboard height, and therefore even the slightest wave will overtop the moraine dam. A large wave would very likely cause scouring of the channel, which would, in turn, lead to catastrophic drainage of the lake. Despite the recent field survey (Rounce et al. 2016) which confirmed the urgent need for mitigation strategies, none have been put in place.

Limitations

The major limitation of this methodology is its inability to determine, with full accuracy, the integrity of a moraine dam structure. While the 15m resolution DEM used in this study is significantly higher resolution than previous remote sensing studies, which primarily rely on the 30m GDEM, some smoothing of dam features is expected to occur. The second major limitation of this methodology is the lack of a robust dataset of GLOF events to statistically validate the model, due to the lack of frequency historically associated with GLOF.

Next Steps

This study utilized a simplified method of mass movement potential, using slope and landcover to quantify potential, rather than the, comparatively, computationally expensive and time-consuming process of using modified single flow models used in other remote hazard analysis (Huggel et al. 2003; Rounce et al. 2016; Prakash and Nagarajan 2017). This allowed for the more efficient analysis of a larger study area, while still accounting for the largest driver of GLOF in the model. A comparative study should be conducted to quantify the difference in sensitivity between the two methods.

Additionally, refining the model to use a shorter time period for lake expansion than the 19-year rate used in this study will allow for the use of newer sensors, such as the Sentinel 2 system, to be used in place of the Landsat sensors. This is advantageous as Sentinel 2 carries instruments capable of significantly higher spatial resolution, thus increasing the accuracy of the model. Given the increasingly rapid pace of change in the region, this shorter time period allows for repeated modeling to more accurately capture the effects of climate change on GLOF hazard.

As hazards increase, it is vital to be able to quantify the downstream impacts of an outburst event. Leveraging the volume measurements calculated in this study future studies can accurately model downstream flooding events. This is a significant area to understand, as the potential of one GLOF triggering a downstream outburst is high in several areas of this study region, being Lumding Tsho (Rounce et al. 2016) and Gokyo. The settlement of Gokyo, on the banks of a lake, is situated on the lateral moraine of Ngojump glacier, has a hazardous lake to the north. Were this lake to have an outburst event, the flow would likely trigger a second outburst from Gokyo lake as well as decimate the settlement.

6. Conclusion

This study prepares a manually delaminated glacial lake inventory encompassing two decades of the upper Duh Kosi watershed sing freely available remote sensing data. Using the limited bathymetric data available, a Monte Carlo simulation aids in creating a linear model for the estimation of glacial lake volumes based on the surface area. This data shows that the total area of glacial lakes in the study area increased 34% over 19 years, with the total volume of water increasing 42%. In the same period, the area of supraglacial lakes increases 303%.

Leveraging an AHP weighting matrix to create a multivariate model, the glacial lakes which, as of 2019, have a surface area greater than .1km^2 are analyzed to determine their susceptibility to an outburst event. Of these twenty-six lakes, four are categorized as very high and four as extreme susceptibility. These levels are predicted to increase in the coming years, as well as the size of the resultant floods. Of the four glacial lakes in the extreme classification, only one, Imja Tsho, has been extensively studied and mitigated. More work needs to be done to fully understand the risks posed by the other lakes, especially Lumding Tsho, the largest and most vulnerable lake in the region.

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Tables

Table 1: Summary of Data

Class of Data	Identifier	Geographic Extent	Native Resolution	Source
Elevation Datasets	Vericon Photogrammetry DEM	Washburn Everest Map	1m	National Geographic Society
	High Mountain Asia DEM	Entire Study Area (voids)	8m	National Snow and Ice Data Center
	SRTM non-void filled	Global	30m	USGS
Weather/Climate Datasets	EarthPulse Station Network	Local	N\A	National Geographic Society
	ERA-5	Global	30km	Copernicus
Imagery	Landsat 5, 7, 8	Global	30m	USGS

Table 2: Index Values

Index Value	1	0.5	0.25
Lake Area	0.1 km^2	NA	NA
Lake Growth	> 100%	50 - 100%	< 50%
Distance from Glacier	In Contact	0--500m	> 500m
Slope from Glacier	> 21^{o}	12^{o} - 21^{o}	< 12^{o}
Distal Slope	> 20^{o}	12^{o} - 21^{o}	< 12^{o}
Dam Width to Height	< 0.1	0.1-0.5	> 0.5
Crest	< 10m	10 - 60m	> 60m
Freeboard	Surface Drainage	< 5m	> 5m
Mass Movement Potential	High	Moderate	Low
Cloudburst	Frequent	Sporadic	Unlikely
Seismic Zone	Frequent	Sporadic	Unlikely

Table 3: AHP Model Outputs

ID	Area (km^2)	Volume Est (m^3)	Below 5400m	Lake Growth	Slope to Glacier	Dist to Glacier	Distal Slope	Width to Height	Crest Width	Freeboard Height	Mass Movement Potential	Seismic	Cloudburst	Hazard
1*	1.358	100275991	1	102	In Contact	0	2.58	0.03	10	0	0.75	0.75	0.5	0.813
2	0.455	18814797	1	-0.5	8.55	4800	6.62	0.08	50	20	0.5	0.75	0.5	0.443
3	0.102	1894089	1	New Lake	In Contact	0	31.92	0.49	23	2	0.5	0.75	0.5	0.700
4	0.147	3335538	1	0	0.00	NoGlacier	2.29	0.02	33	3	0.5	0.75	0.5	0.533
5	0.350	12602756	1	4.8	14.68	1600	8.70	0.09	50	24	1	0.75	0.5	0.585
6	0.505	22089618	1	-15	9.98	3000	24.84	0.15	60	31	1	0.75	0.5	0.668
7	0.129	2721970	1	-21	0.00	9999	27.29	0.17	225	40	1	0.75	0.5	0.568
8	0.133	2869446	1	1.47	16.80	1300	0.06	0.05	500	40	0.25	0.75	0.5	0.388
9	0.131	2809079	1	20	20.46	725	23.75	0.40	19	3	0.5	0.75	0.5	0.500
10	0.357	12968362	1	8.6	In Contact	0	2.75	0.02	90	12	1	0.75	0.5	0.768
11	0.397	15285202	0	13.97	29.98	427	14.74	0.18	57	2	0.75	0.75	0.5	0.590
12	0.190	4962040	0	17.23	28.81	250	2.58	0.03	29	1	1	0.75	0.5	0.733
13	0.245	7297310	1	29	5.60	3000	7.97	0.08	14	4	0.25	0.75	0.5	0.470
14	0.286	9249528	1	0.95	7.29	490	4.00	0.03	29	5	0.5	0.75	0.5	0.495
15	0.129	2725601	0	-0.36	12.30	158	7.97	0.09	17	2	1	0.75	0.5	0.638
16	0.181	4602818	1	13.8	7.52	2100	11.75	0.04	393	3	0.5	0.75	0.5	0.463
17	0.597	28488683	1	0	27.56	500	16.12	0.28	295	8	1	0.75	0.5	0.613
18	0.145	3283472	1	22.5	15.64	650	14.04	0.17	15	4	0.25	0.75	0.5	0.408
19	0.723	38250420	1	6.24	39.79	460	10.43	9.30	6	8	1	0.75	0.5	0.627
20	0.141	3119453	1	20.7	19.34	400	14.90	0.20	59	4	0.5	0.75	0.5	0.493
21	0.262	8102669	1	7.75	22.93	731	23.61	0.33	32	10	0.25	0.75	0.5	0.443
22+	1.165	79328547	1	68.4	In Contact	0	6.33	0.10	20	0	1	0.75	0.5	0.810
23	0.296	9758871	1	6.6	20.46	577	24.99	0.35	99	26	0.5	0.75	0.5	0.460
24	0.247	7369729	1	14.2	42.92	245	21.01	0.33	35	1	1	0.75	0.5	0.743
25	0.212	5849966	1	3.8	38.94	500	9.76	0.05	3	6	1	0.75	0.5	0.753
27	0.113	2226129	1	16	35.30	820	23.99	0.31	38	13	0.25	0.75	0.5	0.450

*+ = Lumding Tsho, * = Imja Tsho*

Figures

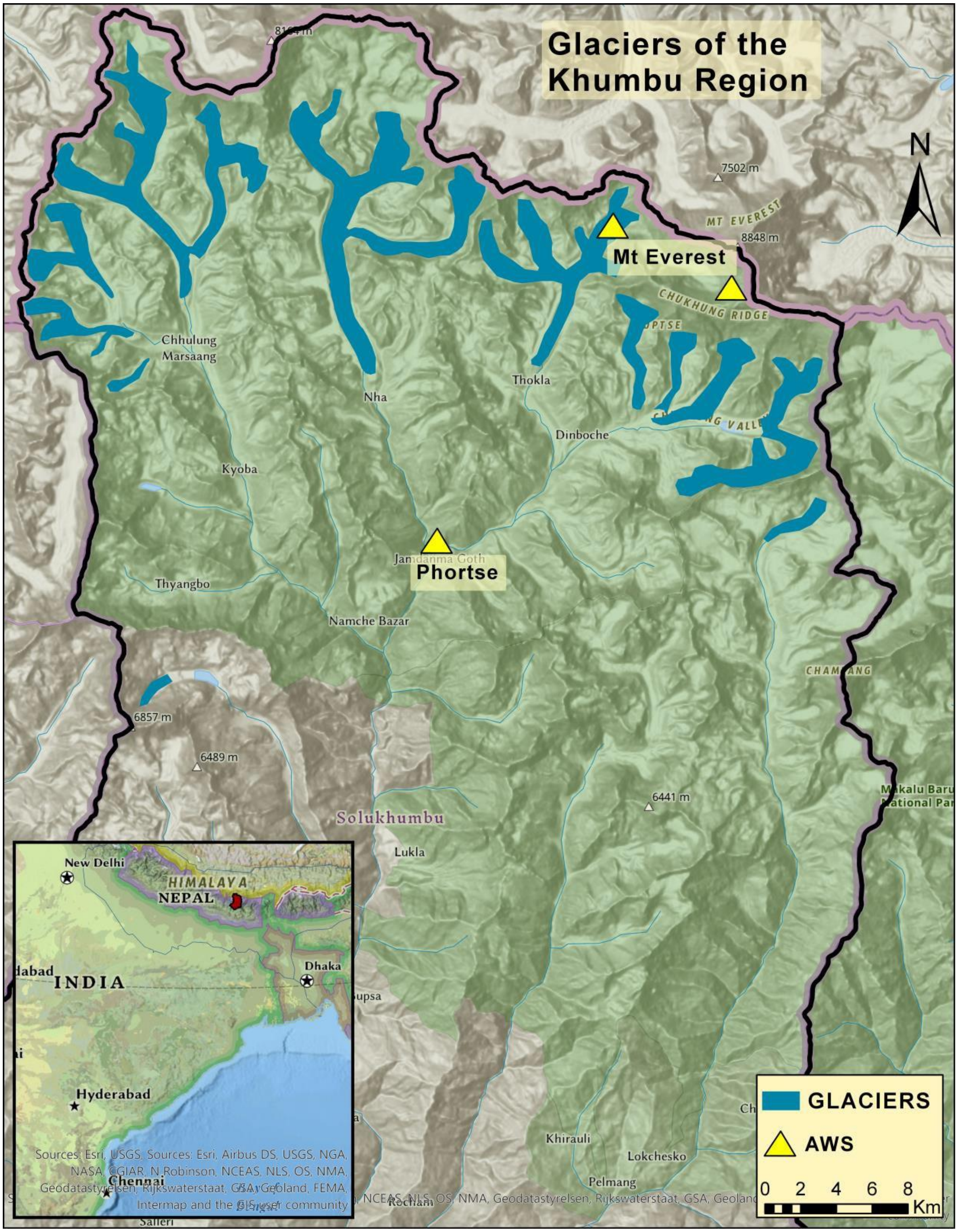


Figure 1: Study area with major valley glacier extents derived from 2019 imagery. National Geographic Society Automatic Weather Stations are shown as triangles. The three AWS on Mt. Everest are displayed as one triangle.

Figure 2 Lake Delineation Workflow

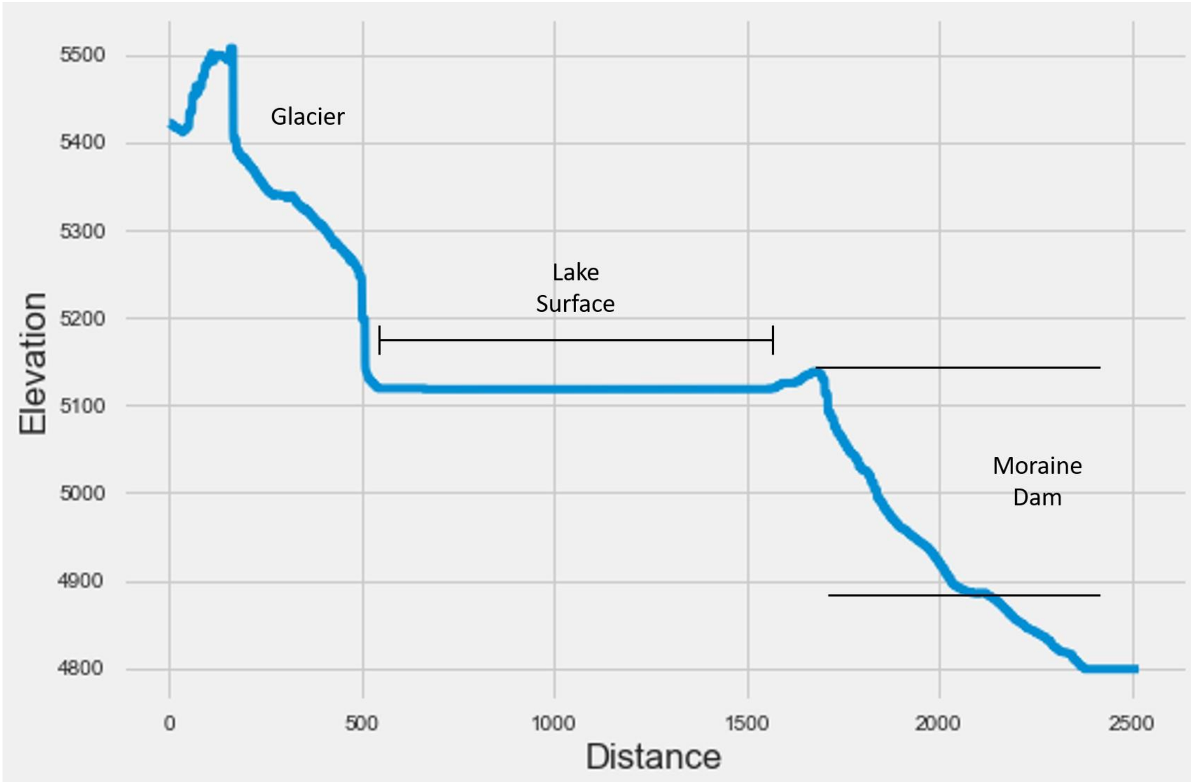
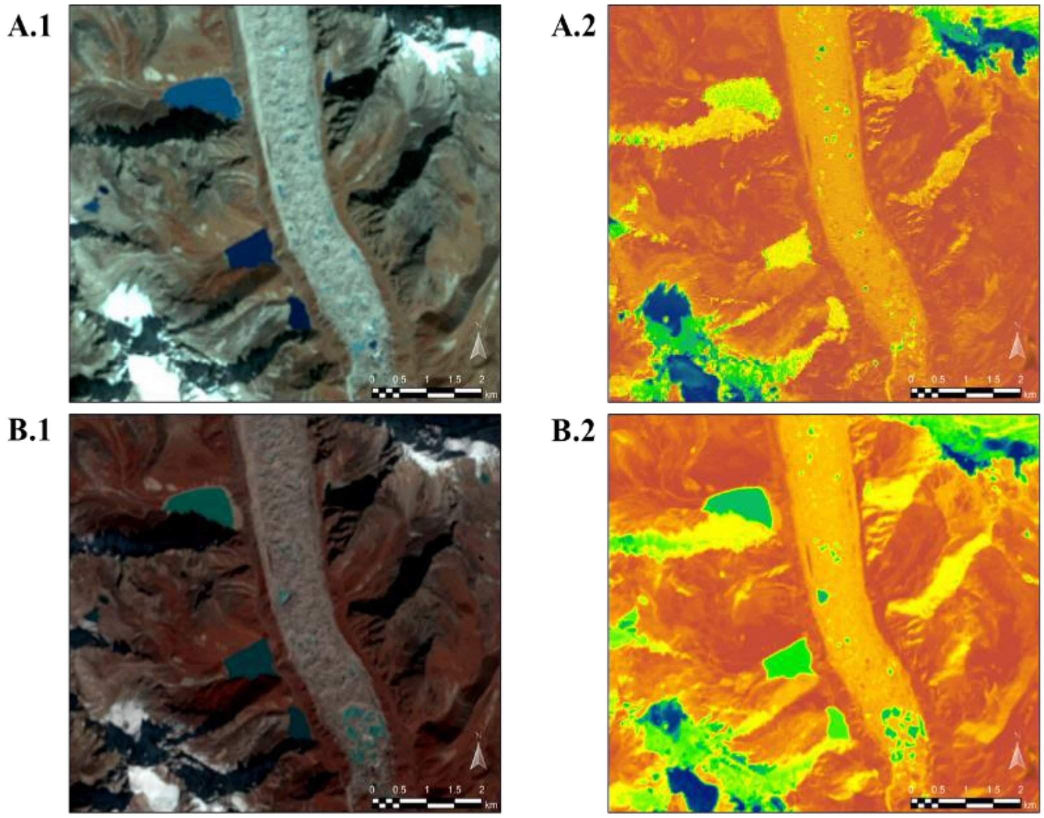


Figure 3 Elevation Profile taken from a transect of Lumding Teng Tsho. While this profile shows substantial freeboard height, Lumding Teng Tsho experiences surface drainage in another area of the Moraine dam. This points to the necessity of multiple transects being evaluated.



Percent Change (2000-2019)	Supraglacial	Other	Total
Est. Volume	NaN	+42%	+42%
Area	+303%	+27%	+34%

Figure 4: Glacial Lake Expansion, Ngojumpa Glacier. Images on right are MNDWI images used highlight lakes present on the glacier. Image set A are 2000 images, image set B are 2019 images. The expansion of supraglacial ponds is seen at the terminus of the glacier. These ponds, as they expand, are merging into a larger terminal lake, a potential hazard in the coming years.

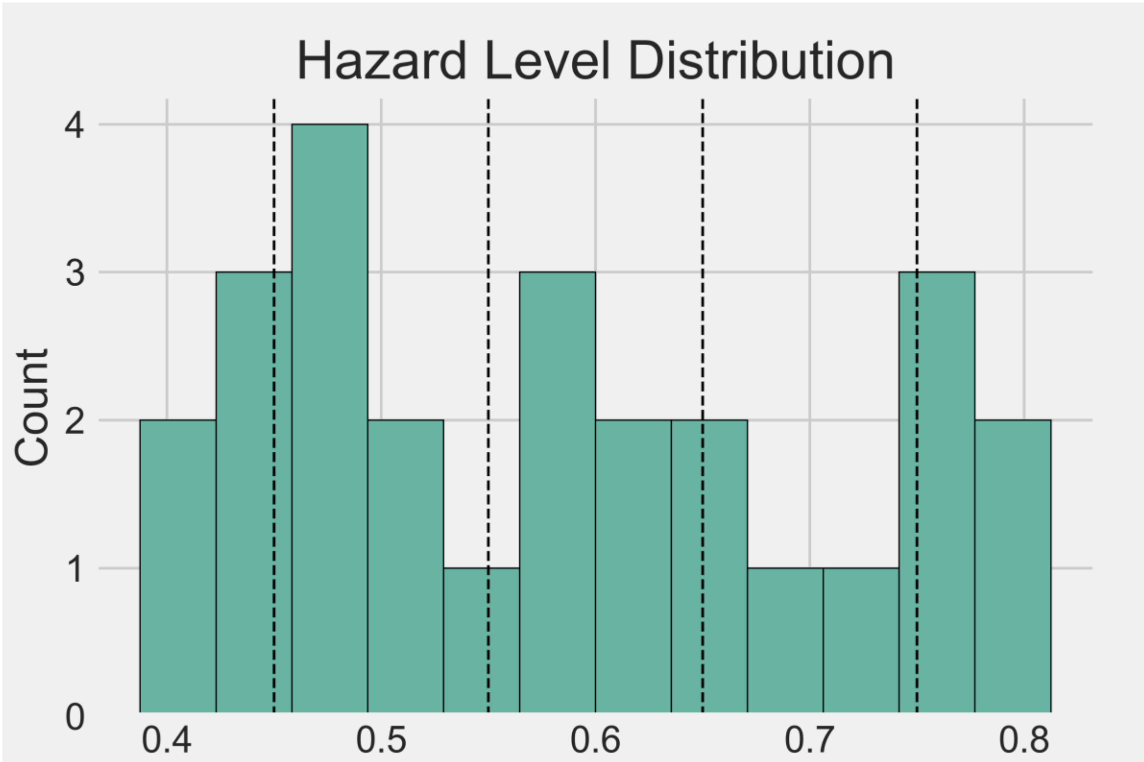


Figure 5: Distribution of GLOF hazards. Dashed line represent classification cut offs, moderate to extreme moving left to right, Four lakes fall into the very high and extreme risk potential classification, respectively.

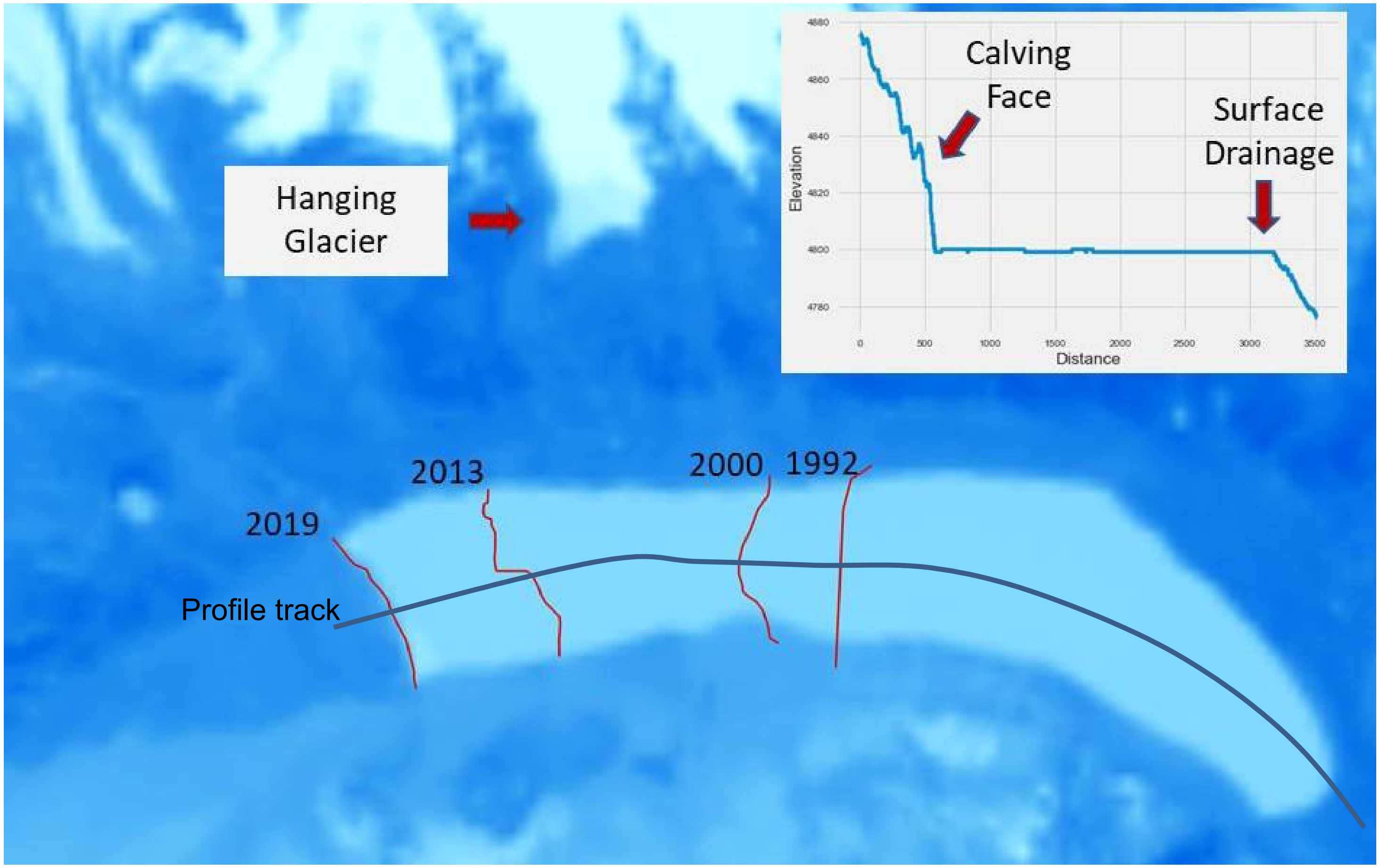


Figure 6: Lumding Tsho pictured with moraine dam on far right. Image is MNDWI computed from 2019 Landsat 8 imagery. Vertical lines represent the caving face of Lumding glacier at the labeled dates, while the horizontal line represents the transect of the elevation profile, Lumding glacier has increased its rate of retreat by 77% in recent years.

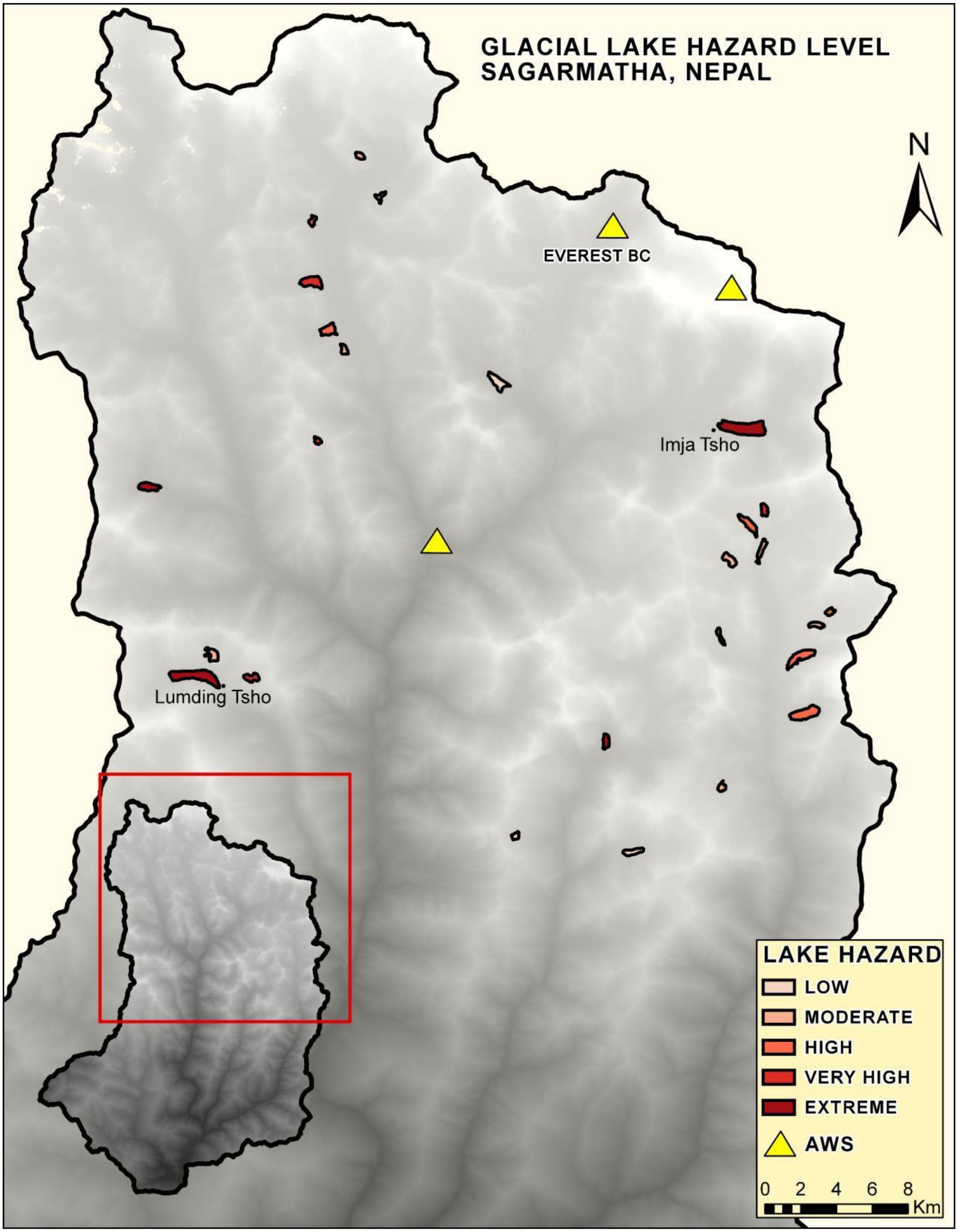


Figure 7 Map of Glacial Lakes and Associated Hazards.

Equations

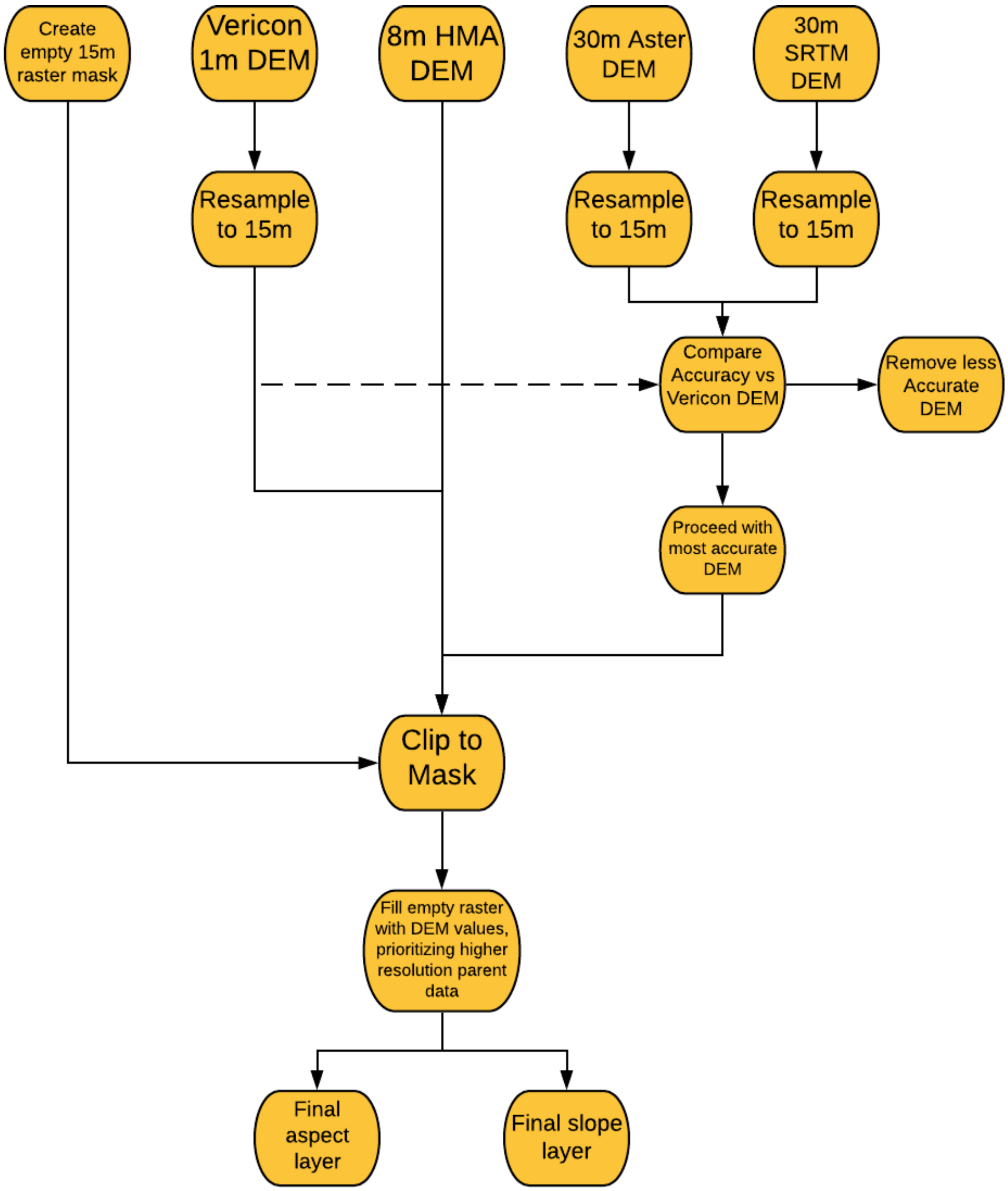
$$y = 0.5305x - 1.2088$$

Equation 1: Linear equation to estimate depth based on area, where y is depth, and x is area. Note this equation is in the base 10 log space

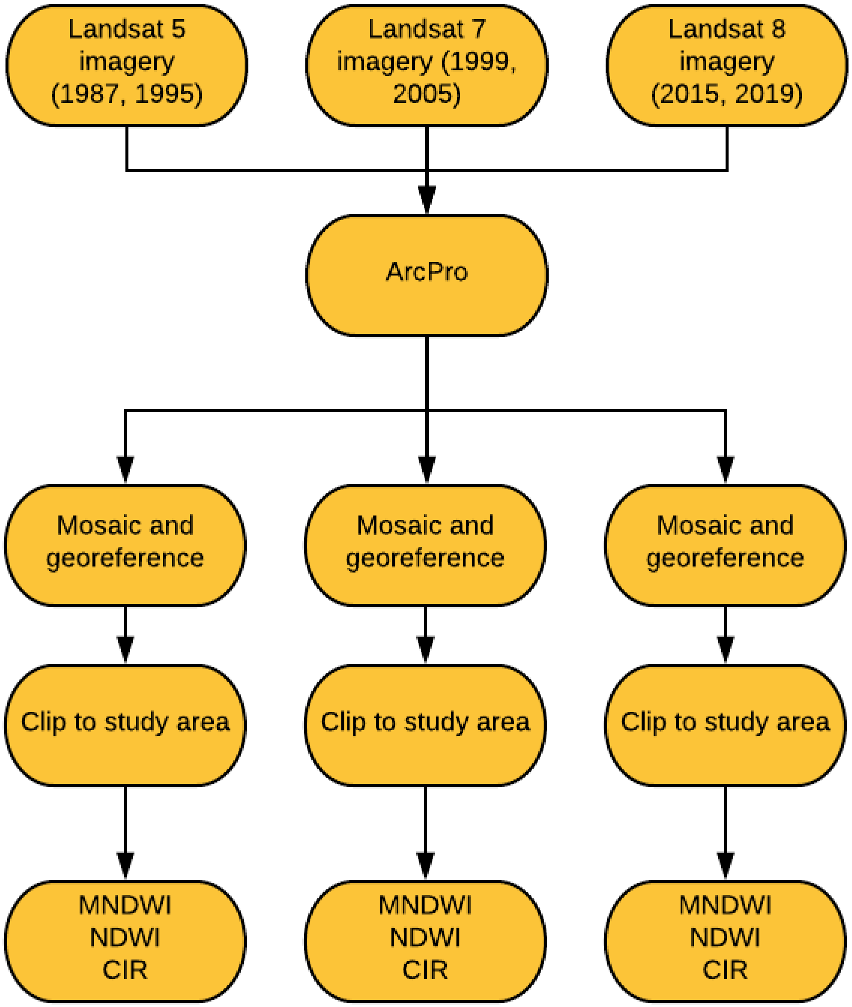
$$MassMovement(.25) + Lake\ Growth(.13) + Freeboard(.12) + Dist\ to\ Glacier(.09) + Cloudburst(.08) + Width\ to\ Height(.07) + Slope\ to\ Glaicer(.07) + Distal\ Slope(.06) + Area(.05) + Seismicity(.04) + Crest(.04) = Hazard$$

Equation 2: AHP model equation with weight values used in Prakash & Nagarajan 2017. i.e. Variable(weight)

Appendix A – GIS Workflows



DEM Workflow



Landsat Imagery Workflow

Vita

Alex O'Neill was born in Chicago, IL to William O'Neill and Paula Mastrangelo. After his family relocated to Cary, North Carolina, Alex graduated from Cardinal Gibbons High School with honors and enrolled in the University of North Carolina at Charlotte to pursue a degree in Mechanical Engineering. Soon after beginning, Alex discovered his passion for the environmental sciences and joined the Earth Sciences program.

In 2017, Alex transferred to Appalachian State University to combine his passion for environmental research with his love for outdoor pursuits such as rock climbing and mountaineering. Alex graduated with a Bachelor of Science in Geography in the fall of 2018, and immediately enrolled in the Cratis D. Williams School of Graduate Studies to pursue a Master's degree in Geography under Dr. Baker Perry.

Throughout his academic career, Alex has held a diverse array of positions, including expedition photographer, Unmanned Aerial Vehicle based research technician, graduate research assistant, and adjunct lecturer. He has also worked as an arborist, general and renovation contractor, whitewater raft guide, and a backcountry wilderness sawyer. He maintains a USFS Class B Sawyer and Axmen certification alongside NOLS Wilderness First Aid and CPR certifications. He has also been involved in several international field campaigns in alpine environments, as well as fieldwork in his home of the Southern Appalachians, and assisted with the analysis of data collected during the National Geographic and Rolex Perpetual Planet Expedition to install the world's highest weather station.

Alex currently resides in Boone, NC, with his partner Jess and their dog, where he has accepted a position as a lecturer in the Geography and Planning Department beginning in August 2021.