ASSESSMENT OF GLACIER VOLUMES AND GLACIAL LAKE CHANGES IN THE HIMALAYAN CONTEXT

A DISSERTATION

Submitted in partial fulfillment of the

requirements for the award of the degree

Of

INTEGRATED MASTER OF TECHNOLOGY

In

GEOLOGICAL TECHNOLOGY

Submitted by:

ANISHA GODHA

DEPARTMENT OF EARTH SCIENCES

INDIAN INSTITUTE OF TECHNOLOGY

ROORKEE ROORKEE-247667 (INDIA)

MAY, 2018

DECLARATION OF AUTHORSHIP

I, **Anisha Godha**, hereby solemnly declare that the work presented in the project, entitled "**ASSESSMENT OF GLACIER VOLUMES AND GLACIAL LAKE CHANGES IN THE HIMALAYAN CONTEXT**" is submitted by me for partial fulfillment of requirements for award of the degree of Master of Technology in Geological Technology to the Department of Earth Sciences, Indian Institute of Technology Roorkee, is an authentic record of my work carried out during the period of May, 2017 to May, 2018 under the joint supervision of **Dr. Anil Kulkarni**, Divecha Center for Climate, Indian Institute of Science Bangalore and **Dr. Ajanta Goswami**, Department of Earth Sciences, Indian Institute of Technology Roorkee.

The matter embodied in this project has not been submitted by me for award of any other degree of Indian Institute of Technology, Roorkee or any other institute.

Date: 4th May, 2018

Place: Roorkee

ANISHA GODHA
Integrated M. Tech. (Geological Technology)
Enrolment number: 13311002
Department of Earth Sciences
IIT Roorkee

This is to certify that the above statement made by the candidate Anisha Godha, is correct to the best of my knowledge.

DR. AJANTA GOSWAMI
Assistant Professor
Department of Earth Sciences
IIT Roorkee

CANDIDATE'S DECLARATION

I, **Anisha Godha**, hereby declare that this written submission represent my own ideas and words. Wherever I have used the ideas or words of others, I have duly cited and referenced the original sources. I also declare that I adhered to all the principles of academic honesty and integrity, and have not misinterpreted and fabricated or falsified any information in my thesis and I realize that doing so will result in disciplinary action from the institute or the sources which have not been properly cited or from whom adequate permission has not been taken.

Date: 4^{th} May, 2018 **ANISHA GODHA**

ACKNOWLEDGEMENT

I feel immense pleasure and delectation to express my deep sense of admiration to those people who have helped, motivated and encouraged me for the successful completion of my project.

I would like to extend my gratitude to Dr. Anil Kulkarni, Divecha Center for Climate Change, Indian Institute of Science Bangalore, for mentoring me and for his valuable feedback that served as a constant inspiration.

I would like to express my deep sense of obligation to Dr. Ajanta Goswami for his kind support and guidance throughout my project. I wish to acknowledge, with gratitude, Professor Sunil Bajpai, Head of Department (HOD), Department of Earth Sciences, for the continued support.

I would like to extend my humble gratitude to Ms. Remya Namboodiri and Mr. Pradeep Srinivasalu, Divecha Center for Climate Change, Indian Institute of Science Bangalore, without whom, it wouldn't have been feasible for me to effectively accomplish the objective. Special thanks to Mr. Shashank Bhushan, Indian School of Mines Dhanbad and Mr. Bijoy Ketan Mohanta for their constant assistance.

Finally, I would like to acknowledge all my friends and family for being consistently supportive.

ANISHA GODHA

CONTENTS

ABSTRACT

The Satluj River originates near Manasarovar Lake and flows through Tibet, before entering India at Shipki La pass. The river flows west-southwest through the states of Himachal Pradesh and Punjab, where Beas river confluences with the Satluj river. Satluj river is fed by the glacier melt, snow melt and rain, and is considered to be the life line of Northern India, providing water for irrigation canals and a number of hydro-electric power projects like Bhakra-Nangal, Nathpa Jhakri, Kol dam and Baspa Hydel Project. The Satluj and Beas basins consist of 2018 and 469 glaciers with glacierized areas of 1433 ± 71 km2 and 499 ± 25 km2 respectively. The Parbati basin consists of 279 glaciers and has a glacierized area of 395 km2. In the future, however, the glaciers in the basin are going be altered due to fluctuations in the climate. Basin scale assessment of the glacier volume in these reservoirs is crucial to assess the future changes in mass loss, melt runoff and hydro-electric potential. Hence in this study, the volume of glaciers in Parbati, and Satluj and Beas basins of the Himalaya are estimated using the automated laminar flow model and scaling equation.

Himalayan glaciers are the important source of fresh water for innumerable rivers that flow to the major rivers like Indus, Ganga and Bramaputra. To understand sustainability of this source under climate change scenario, we need proper estimate of glacier stored water. Glacier areal extent can be obtained using remote sensing techniques and numerous inventories are now providing reliable data, however depth measurements are difficult and generally obtained using scaling method. The scaling methods can provide large errors in volume estimates in the Himalaya, as limited availability of field data. This provides large uncertainties in the volume estimates. Therefore, a model based upon surface velocity, slope and laminar flow of ice was used to estimate spatial distribution of glacier depth in Parbati, Satluj and Beas Basins, Himachal Pradesh, India.

The volume of the glaciers can be derived by using a laminar flow model with glacier surface velocity and slope derived from remote sensing images. Glacier surface velocities are obtained by sub-pixel correlation of consecutive year image scenes and slope is estimated from a digital elevation model at 100 m contour intervals. The thickness is initially obtained over multiple flowlines drawn on the glacier and then interpolated using thin plate spline interpolation over the entire extent of the glacier. Based on this approach, an automated modeling of glacier volume and ice thickness distribution is done in Python. Currently this model is applicable to glaciers for which uniform velocity fields are available.

The thickness distribution of 298 glaciers are estimated by using the model in Satluj and Beas Basins, which cover an area of 588 ± 29 km2 and have an estimated volume of 27.5 ± 5 km3. However, large area of the basin is occupied by smaller glaciers and due to the presence of cloud cover, velocity field are not available for all glaciers. Hence, the volume of the other glaciers is computed by developing an empirical volume area scaling equation. A power law relation is derived between the area of the glaciers and volume estimates from the laminar flow model area and volume of the glacier, with scaling exponent $\lambda = 1.2869$. The total amount of glacier stored ice in Satluj and Beas basin is equal to 84 ± 15 Gt, obtained from modelled and statistically upscaled estimates of glacier volumes. The power law relation derived for Parbati basin gives a scaling exponent 1.2136. The total glacier stored water of the 155 glaciers in Parbati basin, which covers an area of 377.16 km^2, is estimated as 21.07 km^3.

PART A

ESTIMATING GLACIER VOLUMES

Chapter 1

Introduction

5.1 Relevance of glaciers in a changing climate

Glaciers are nature's one of the most fascinating creations, which are located in the most remote places on earth. Most of the glaciers are located either in high altitudes or high latitudes. The best stated example for high altitude glaciers is the Himalaya. The Himalaya, extending over a stretch of 2500 km2 popularly known as the third pole (Bolch et al.,2012), for its total of around 12,000 glacier, which counts for the third maximum glacial coverage apart from the Antarctic, and Greenland (Yao et al.,2012). There is a wide variation of glacial coverage within the Himalayan stretch, biasing maximum coverage located towards its north western part in the Indus basin and western Ganga and their respective sub-basins. The dynamic nature of the Himalayan glaciers can be well understood by their behavior in terms of its change in mass balance (Gardelle et al.,2011), which over the last few decades, is showing enormous variations. It is evident that since the mid-19th century, the Himalayan glaciers are showing cumulative length reduction except a few in the Karakoram and the other north-western mountain ranges (Bolch et al.,2012). These evidences provide good proxies to understand the impact of climate change over the Himalayan glaciers.

A prime signature of glacier retreat is the formation of glacial lakes at higher altitudes and its types is governed by its location. A proglacial lake is located at the tongue of the glacier, most often dammed by glacial deposits called end moraines, whereas a supraglacial lake is one which has its location on top of glacial body. Other types of lake include erosional lakes, blocked lakes, cirque lakes etc. Thus a glacial lake is defined as a water mass existing in a sufficient amount and extending with a free surface in, under, beside, and or in front of a glacier and originating from the glacier activities or/and retreating processes of glacier (Campbell and Pradesh,2005).ICIMOD 2007 suggested the possible cause glacier melts due to increase in average surface temperature of Earth between 0.3 ºC to 0.6 ºC over the past hundred years. IPCC in 2007 reported that there will be an increase in temperature in the Himalayan region between 1 to 6°C by 2100. As a result of this more glacier will melt and snow cover would decrease between 43 to 81 percent leaving behind many more glacial lakes in future (Narama et al.,2010).The majority of glacial lakes are formed by damming of unsorted and unstable moraines. Occasionally these moraine dam breaches due to several factors, which results in sudden release of tremendous amount of stored water along with glacial debris, 9 causing serious flood along the downstream part of river channel. This phenomenon is called Glacial Lake Outbrust Flood (GLOF) and causes massive damage to human settlement, infrastructures, natural resources and farmlands (Banerjee,2013) Therefore, a strong need to monitor these glacial lakes for their formation, expansion and vulnerability (Richardson and Reynolds ,2000;Thompson et al.,2012;Worni et al.,2012).

Glaciers can potentially be a source for many hazards in the Himalayas, especially in lieu of their widely reported retreat as a response to climate change. Alongside such retreat processes, there is a huge reported increase in the number of potentially dangerous moraine dammed glacial lakes in the Himalayas. Such lakes can form from melting in the ice body enclosed by moraine deposits, both lateral and end, and through various other mechanisms, and have a huge potential to burst disastrously. There have been evidences of discharge rates as high as 30,200 m3/s and run-out distance greater than around 350m in case of such outburst floods. However, even with the prospects of such risks, mitigation of such glacial lakes is feasible (Richardson and Reynolds, 2000).

5.2 Monitoring and predicting glacier changes

Assessment of a glacier's health for many glaciological and hydrological studies requires ice volume and thickness distribution of a glacier as important parameters. Technically, ice volume is defined as the amount of water stored by a glacier in a given drainage basin. A more apt parameter is the ice thickness distribution of a glacier within its glacial boundary which can have important influence over the hydrological characteristics of the catchment area in which it lies. Studies which address the effect of climate change on glacial retreat in high alpine catchments (e.g. Huss et al., 2008) and even glacio-dynamical models (e.g. Hubbard et al., 1998) essentially rely on ice volume or ice-thickness as an initial parameter.

Traditionally, many techniques have been used in the past for measuring ice thickness at a given point location, like radio-echo soundings and borehole measurement techniques. However, field measurement of ice volume is often marked by topographical constraints like harsh weather conditions and irregular terrain which limit such studies, which are also expensive and laborious. Moreover, the volume of ice cannot be determined directly, but is obtained from inter- and extrapolation of direct thickness measurements.

Volume/area scaling methods have therefore been used to estimate mean depth or volume of ice due to the limitations posed by field studies. They serve as a better alternative approach for large glacier samples as they use easily available datasets. Thus the total volume of glaciers is commonly estimated using such volume-area scaling relations at present (Erasov, 1968; Macheret and Zhuravlev, 1982; Muller et al., 1976; Bahr et al., 1997).

Many attempts have been made in the past to infer mean depth of ice or its distribution from surface parameters. Applications of shallow ice-approximation (Paterson, 1970; Haeberli and Hoelzle, 1995) and other complex methodologies like inverse methods based on modeling (Thorsteinsson et al., 2003; Raymond, 2007), which emphasize mainly on ice sheets and ice streams are important examples of these. The first such statistical method was based on the estimation of mean depth from surface area (Mu¨ller,1970). Originally for Alpine glaciers, the method has been adopted for Himalayan glaciers as well (Raina and Srivastava, 2008). Sufficient information is available regarding area and length (Chen and Ohmura, 1990; Bahr and others, 1997;Radic´ and others, 2008) which has enabled derivation of empirical relations between glacier volume and glacier area or length or both.

1.3 Objectives and structure of this thesis

This thesis is divided into two parts. The first part focuses on calculation of glacier volumes in the Himalayan context.

In Chapter 1, a new automated modeling of glacier volume and ice thickness is proposed based on laminar flow. Velocity slope methods are convenient, especially for glaciers where mass distribution data is not available, since velocity and slope data can easily be derived from available datasets (satellite imageries from USGS, ASTER DEM data, boundary data from RGI etc). Automating enables calculation of glacier volumes in an efficient way, which otherwise require long and tedious pre-processing for analysis. The accuracy of the model is assessed based on existing measurements and a data validation approach is established.

Chapter 3 and 4 are an application of the model to Parbati, and Satluj and Beas basins, respectively. The developed model is successfully applied to a total of 298 glaciers in Satluj and Beas basins and some of the glaciers in Parbati basin. The inference of ice thickness distribution from the model is addressed first. The calculated volumes are then used to derive a scaling relationship between volume and area for the glaciers in the respective basins. The scaling model is then applied to the remaining glaciers for which direct estimation is difficult due to large snow cover in satellite data. The total amount of glacier stored water and ice are calculated for Satluj, Beas and Parbati basins using the combined methods, automated as well as scaling models.

In the second part, an attempt has been made to understand hazards related to glacial lakes in the Himalayan context. Chapter 5 is a brief overview of Glacial Lake Outburst Floods in the Himalayas In Chapter 6, methodologies related to assessment of glacial lake hazards in the existing scientific literature are reviewed and compiled.

The thesis is concluded with a 'Conclusions and Perspectives' chapter, in which the major findings of the study are outlined and the scope of further research in the area is addressed.

Chapter 2

A method to estimate the ice thickness distribution of glaciers

2.1 Introduction

Assessment of a glacier's health for many glaciological and hydrological studies requires ice volume and thickness distribution of a glacier as important parameters. Technically, ice volume is defined as the amount of water stored by a glacier in a given drainage basin. A more apt parameter is the ice thickness distribution of a glacier within its glacial boundary which can have important influence over the hydrological characteristics of the catchment area in which it lies. Studies which address the effect of climate change on glacial retreat in high alpine catchments (e.g. Huss et al., 2008) and even glacio-dynamical models (e.g. Hubbard et al., 1998) essentially rely on ice volume or ice-thickness as an initial parameter.

Traditionally, many techniques have been used in the past for measuring ice thickness at a given point location, like radio-echo soundings and borehole measurement techniques. However, field measurement of ice volume is often marked by topographical constraints like harsh weather conditions and irregular terrain which limit such studies, which are also expensive and laborious. Moreover, the volume of ice cannot be determined directly, but is obtained from inter- and extrapolation of direct thickness measurements.

Volume/area scaling methods have therefore been used to estimate mean depth or volume of ice due to the limitations posed by field studies. They serve as a better alternative approach for large glacier samples as they use easily available datasets. Thus the total volume of glaciers is commonly estimated using such volume-area scaling relations at present (Erasov, 1968; Macheret and Zhuravlev, 1982; Muller et al., 1976; Bahr et al., 1997). Many attempts have been made in the past to infer mean depth of ice or its distribution from surface parameters. Applications of shallow ice-approximation (Paterson, 1970; Haeberli and Hoelzle, 1995) and other complex methodologies like inverse methods based on modeling (Thorsteinsson et al., 2003; Raymond, 2007), which emphasize mainly on ice sheets and ice streams are important examples of these. The first such statistical method was based on the estimation of mean depth from surface area (Mu¨ller,1970). Originally for Alpine glaciers, the method has been adopted for Himalayan glaciers as well (Raina and Srivastava, 2008). Sufficient information is available regarding area and length (Chen and Ohmura, 1990; Bahr and others, 1997;Radic´ and others, 2008) which has enabled derivation of empirical relations between glacier volume and glacier area or length or both.

In this chapter, a new automated modeling of glacier volume and ice thickness is proposed based on laminar flow. Velocity slope methods are convenient, especially for glaciers where mass distribution data is not available, since velocity and slope data can easily be derived from available datasets (satellite imageries from USGS, ASTER DEM data, boundary data from RGI etc). Automating enables calculation of glacier volumes in an efficient way, which otherwise require long and tedious pre-processing for analysis. The accuracy of the model is assessed based on existing measurements and a data validation approach is established.

2.2 Methodology

3.4.1 Estimation of surface velocity field

Sub-pixel corelation of satellite image data of consecutive years is used for obtaining the velocity vector fields at the surface of the glacier. The velocity vector field is obtained based on the displacement of images in both north-south and east-west direction. This co-registration of satellite images is formally done using a software called COSI-Corr (Co-registration of Optically Sensed Images), which is available for free and can be downloaded from the official website.

Leprince et al. describe the set of algorithms and the underlying mathematical model in detail. The window is slided for getting the best fit for the corelation. The software outputs 3 images after running the data and executing the algorithm: north-south displacement field, east-west displacement field and an SNR field that gives an assessment of the performance of the algorithm. Technically, every pixel that has a signal to noise ratio less than 0.9 and displacement greater than 85 m from pixels linked to the same point in the base image is rejected. Using the two output images a velocity vector is produced for every pixel which is overlain on the base satellite image. All the resultant velocity vectors are then subsequently verified for their alignment and the magnitude of the displacement is then evaluated from the Eulerian norm of the images.

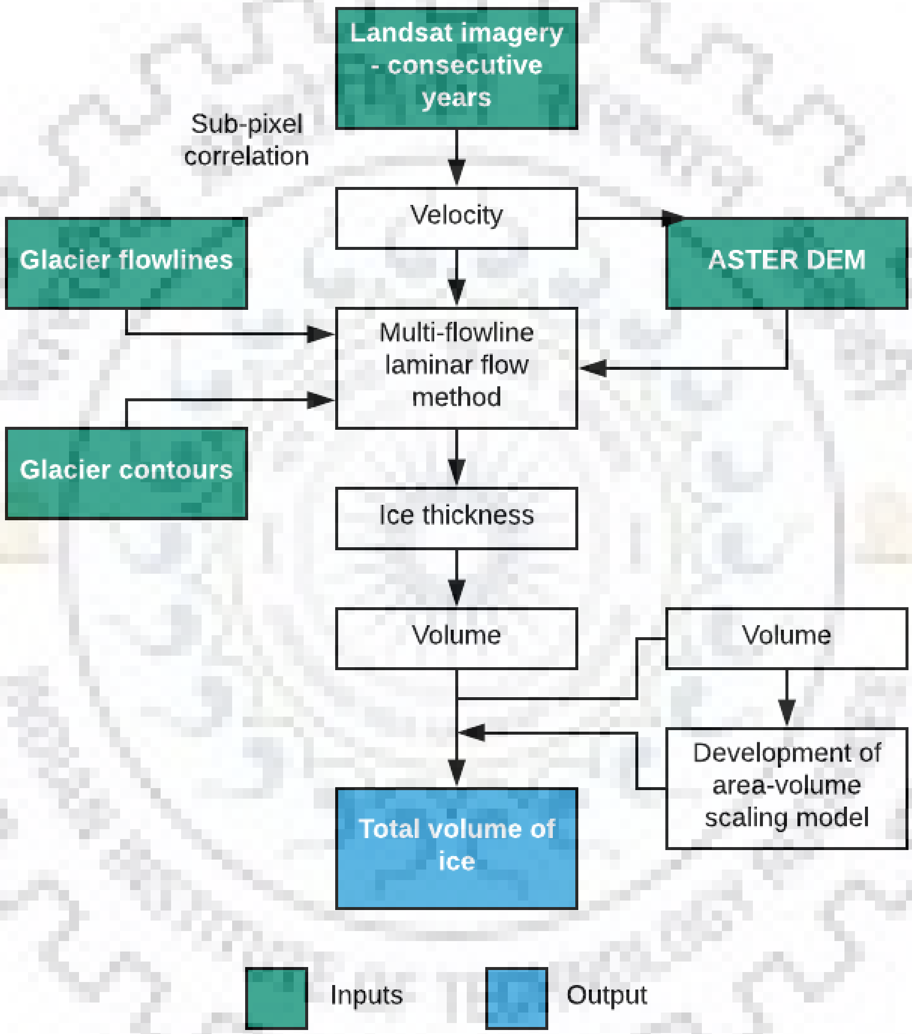


Figure 2.1: Flowchart depicting the laminar flow methodology to estimate ice thickness distribution and glacier volume

3.4.2 Calculation of depth

The laminar flow model method given by Cuffey and Paterson, 2010 is applied to estimate the depth distribution of glaciers based on surface characteristics, like surface velocity. The equation of the ice flow is given by:

$$U_s = U_b + \frac{2A}{n+1} \tau b^n H$$

Where, U_s and U_b are surface velocity and base velocity, respectively Since, there is no reliable information on the values of base velocity for glaciers in the Parbati basin, therefore base velocity is taken to be 25% of surface velocity, whose value is known from sub-pixel correlation of acquired satellite images with the aid of COSI-Corr software.

Glen's flow law exponent is taken to be 3 . H gives the ice depth while A is a creep parameter, and its value is taken to be 3.24 x 10^{-24} $Pa^{-3}s^{-1}$. The value of the creep parameter depends on a number of factors like texture, grain size, sorting, as well as the amount of impurities present in the underlying or overlying layer.

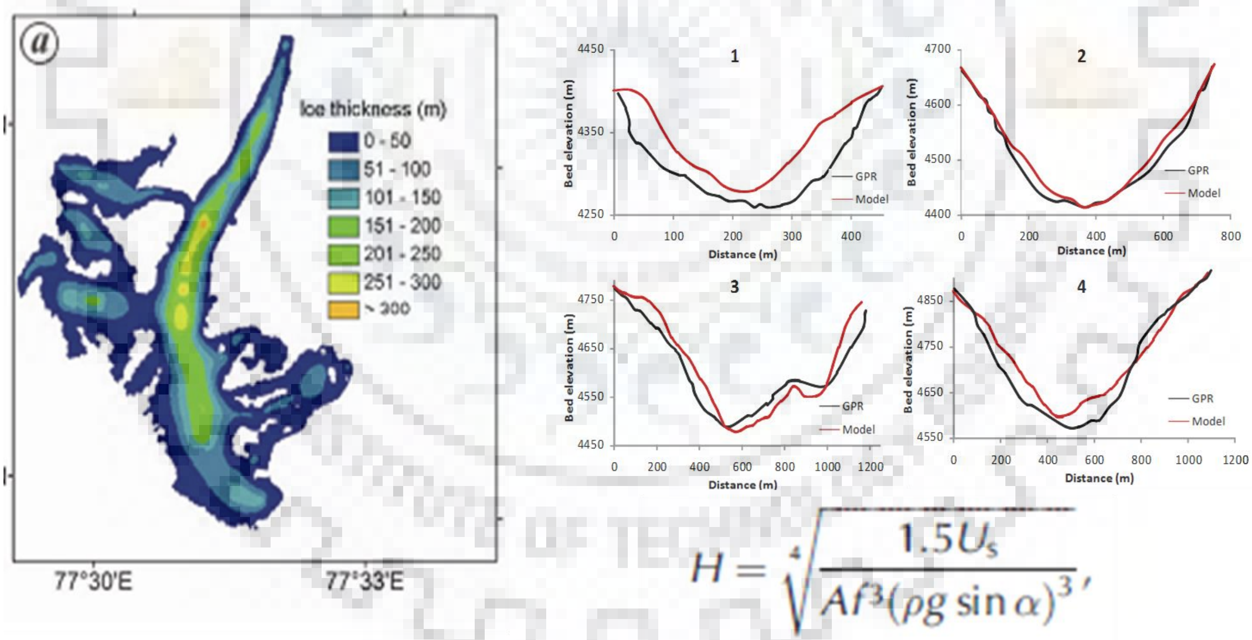


Figure 2.2: An illustration of the validation of the laminar flow model; Cross section profiles are given for the values obtained from field methods i.e. Ground Penetration Radar survey (black) and the model (red) (*Source: Manya et al., 2016)*

The basal stress is given by:

$$\tau b = f \rho g H \sin \alpha$$

Here, ρ is the ice density which is nominally taken as 900 kg/m^3, g is the acceleration due to gravity and is 9.8 m/s^2. F is a scale factor which is the ratio between driving stress and basal stress along a glacier. For temperate glaciers, the scale factor is assumed to lie between 0.8 and 1. For the purpose of our study, f is taken as 0.8. For calculations of slope of the surface of glaciers at a given point location, ASTER Digital Elevation Model contours are used, which are at an interval of 100 m. Since the ice depth in the given locality is of the order of 10 m, this particular interval value being of greater order is apt for the objective of the study.

Equations (1) and (2) can be used to give the value of ice depth, H at a given point location which can give the thickness of the glacier between consecutive 100m elevation contours.

$$H= \sqrt[4]{\frac{1.5U_s}{Af^3(\rho g \sin \alpha)^3}}$$

The thickness values are then plotted to give an ice thickness distribution for all the glaciers in the Parbati basin. Smoothening of the depth values is then done using a 3 by 3 kernel in order to get rid of any erroneous values in the thickness distribution raster.

3.3.2 Uncertainty Analysis

To quantify the uncertainty in the estimated thickness values, take logarithm on both sides of equation 3 and differentiate subsequently:

$$\frac{dH}{H} = 0.25[\frac{dU_s}{U_s} - \frac{dA}{A} - 3\frac{df}{f} - 3\frac{d\rho}{\rho} - 3\frac{d(\sin \alpha)}{(\sin \alpha)}]$$

3.4 Results

Figure 2.2 illustrates the difference map as a qualitative comparison of values obtained from manual method and automated method.

Thickness from manual method

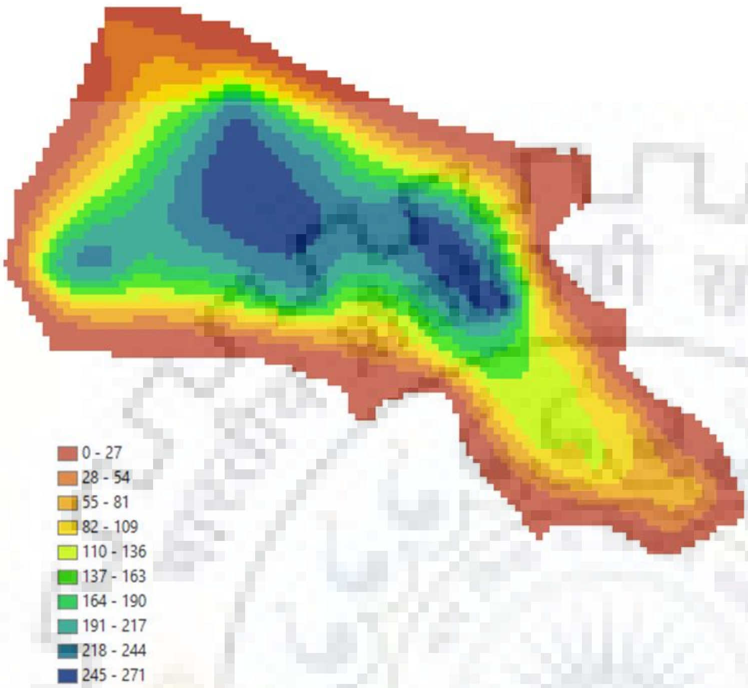


Figure 2.3: Thickness distribution raster for a glacier in Parbati basin from manual methods based on velocity slope model

Thickness from automated method

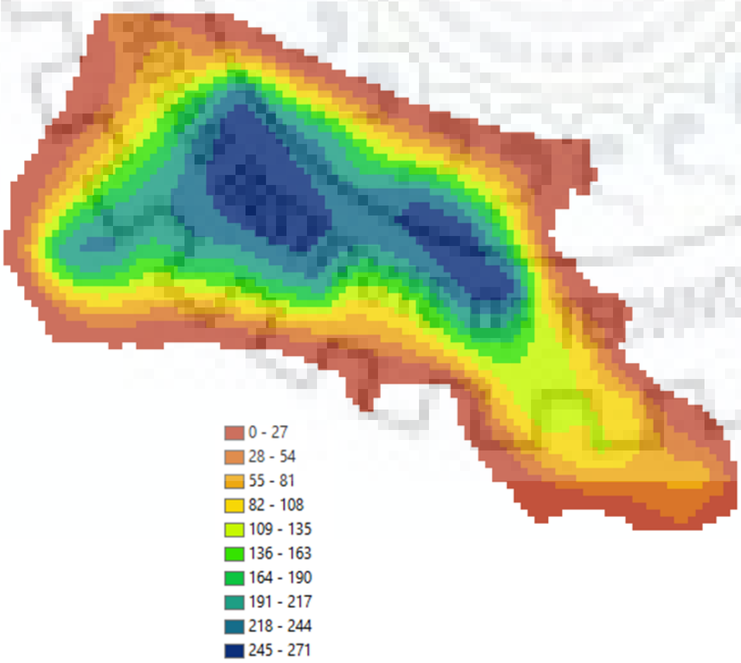


Figure 2.4: Thickness distribution raster for a glacier in Parbati basin using automated modeling

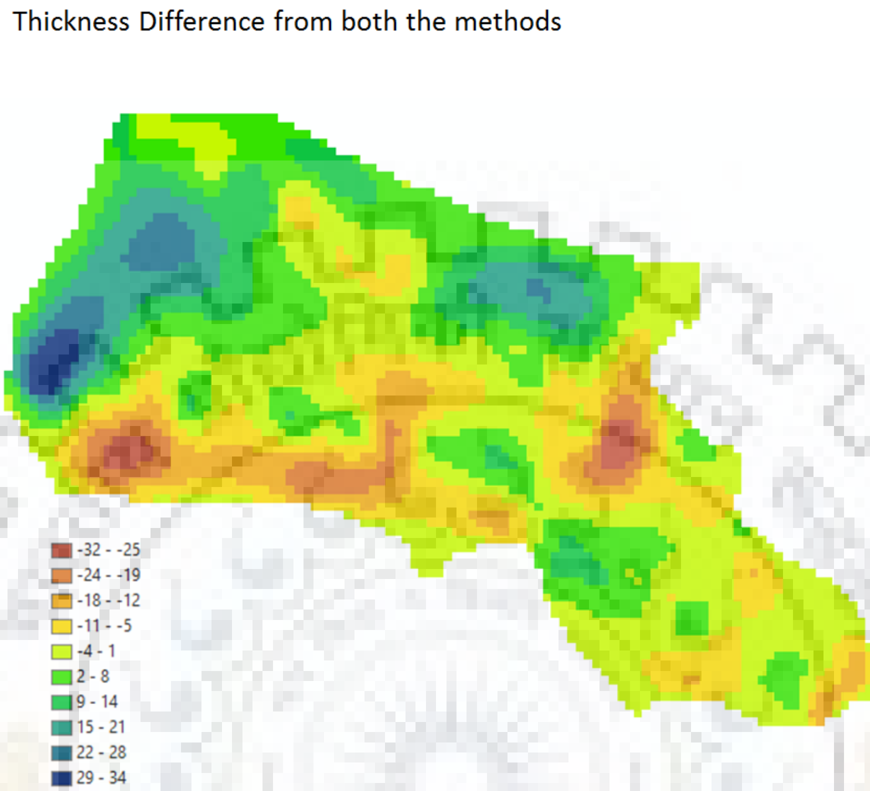


Figure 2.3 Thickness difference map from manual method and automated method

3.5 Conclusions

From this study, the qualitative comparison of automated model and subsequent analysis show that the model can be conveniently and efficiently applied to a large number of basins, and can further be used to establish scaling relationships that are more accurate.

However, more research is required to address other issues in the automation process, like the delineation of flowlines, and the incorporation of estimation of volume to other important fields of study, like calculation of mass balance distribution in the Himalayas and the direct estimation of change in volume extent of glacial lakes based on change in areal extent.

	sum	volume (m3)	In km3
manual	453368.5	408031640.1	0.408032
No. of pixels	4114		
Python	452897.7	407607949.3	0.407608
No. of pixels	4075		
difference	39		0.000424

Table 2.1. Data specification and results; manual and automated method

The python scripting for the automated modeling of glacier volume and ice thickness distribution is given in Appendix A.

Chapter 3

Estimation of glacier stored water in Parbati Basin using scaling and laminar flow model

Citation: Namboodiri, Remya& Kulkarni, A &Srinivasalu, Pradeep &Godha, Anisha&Goswami, Ajanta. (2017). Estimation of glacier stored water using scaling and laminar flow model: A case study in Parbati basin. 10.13140/RG.2.2.21685.27366.

ABSTRACT: Himalayan glaciers are the important source of fresh water for innumerable rivers that flow to the major rivers like Indus, Ganga and Bramaputra. To understand sustainability of this source under climate change scenario, we need proper estimate of glacier stored water. Glacier areal extent can be obtained using remote sensing techniques and numerous inventories are now providing reliable data, however depth measurements are difficult and generally obtained using scaling method. The scaling methods can provide large errors in volume estimates in the Himalaya, as limited availability of field data. This provides large uncertainties in the volume estimates. Therefore, a model based upon surface velocity, slope and laminar flow of icewas used to estimate spatial distribution of glacier depth in ParbatiBasin, Himachal Pradesh India. In the paper we will discuss differences in volume estimates from different techniques.

3.1 Introduction

The Himalayas extend over an area of around 40,000 km2, and therefore constitute one of the largest ice bodies second to the Antarctic and Arctic regions (Bolch et al,, 2012). Himalayan glaciers have therefore been an area of great scientific interest. Many recent scientific studies indicate that the Himalayan glaciers are losing mass at different rates (Kulkarni et al., 2007;Venkatesh et al., 2012). For assessment of any future glacial retreat, an estimate of the current ice volume is the most important initial parameter. Many glacio-dynamical models also rely on ice volume as an initial parameter (e.g. Hubbard et al. 1998).

However, the lack of sufficient data especially about the amount of water stored in the different glaciers and their ice thickness distribution, poses significant difficulties in assessing Himalayan glaciers and their sustainability in the long run (Raina, 2009; Gantayat et al, 2014). There are huge differences in the estimates given on their rates of mass gain and mass balance distribution in scientific literature (Jacob et al., 2012). This severely reduces the feasibility of applying apparent mass balance methods for estimating volume, as have been done elsewhere, for example the Swiss Alps. Moreover, the uncertainties recorded in the characterization of glacier dynamics in the Himalayan and Karakoram region and some of the predictive models are of significant concern because these can have adverse consequences on water resources (Bolch et al, 2012).

In this chapter, an attempt has been made to estimate the total volume of glacier stored water in the Parbati basin using the velocity-slope method given by Gantayat et al., 2014. The chief motivation is the lack of sufficient information on the most critical parameters for characterizing glacial dynamics, viz. glacier volume and surface velocity distribution in this basin. Field studies have been heavily restricted in the Himalayan-Karakoram region due to topographical constraints and irregular weather conditions. The volume of 155 glaciers in the basin is manually calculated using the method.

The estimated volumes are then used to derive an empirical relationship based on power law between volume and area. The physical basis for a scaling relationship between glacier volume and area or length is well documented (e.g. Bahr et al. 1997; Lliboutry, 1987). In fact, many earlier methods were based on statistically estimating the mean depth from surface area (e.g. Muller, 1970). Such empirical methods are essentially inversion models because unknown parameters, like mean depth can be estimated from available data. A lot of the documented work on glacial volumes in the Alpine glaciers is based on the power law behavior. For example, an estimate of the total volume of ice in the Swiss Alps is given by Muller et al. (1976) based on two different power law equations between glacier area and mean depth. The rule has been implemented for a number of Himalayan glaciers. However, the stability of the solutions given by these scaling models has been under scrutiny because these can be very sensitive to non-uniformity in the specified glacier boundary data, making the solution very inconsistent (Bahr et al. 2013).

3.2 Study Area

This study concerns all the glaciers in Parbati basin in Himachal Pradesh. The Parbati basin (Fig. 3.1) is situated in the northern part of the Malwa plateau between 450 and 600 m ASML. It is spread over the districts of Shajapur, Sehore, Rajgarh, Guna and Sheopur in Madhya Pradesh and Kota-Baran region in Rajasthan. Parbati river is a major tributary of Chambal which originates on the northern slopes of Vindhyas at Malegarh (22 56' N, 76 39' E). The volume of glacier stored water is estimated for a total of 155 glaciers in the basin which cover an areal extent of 377.16 km².

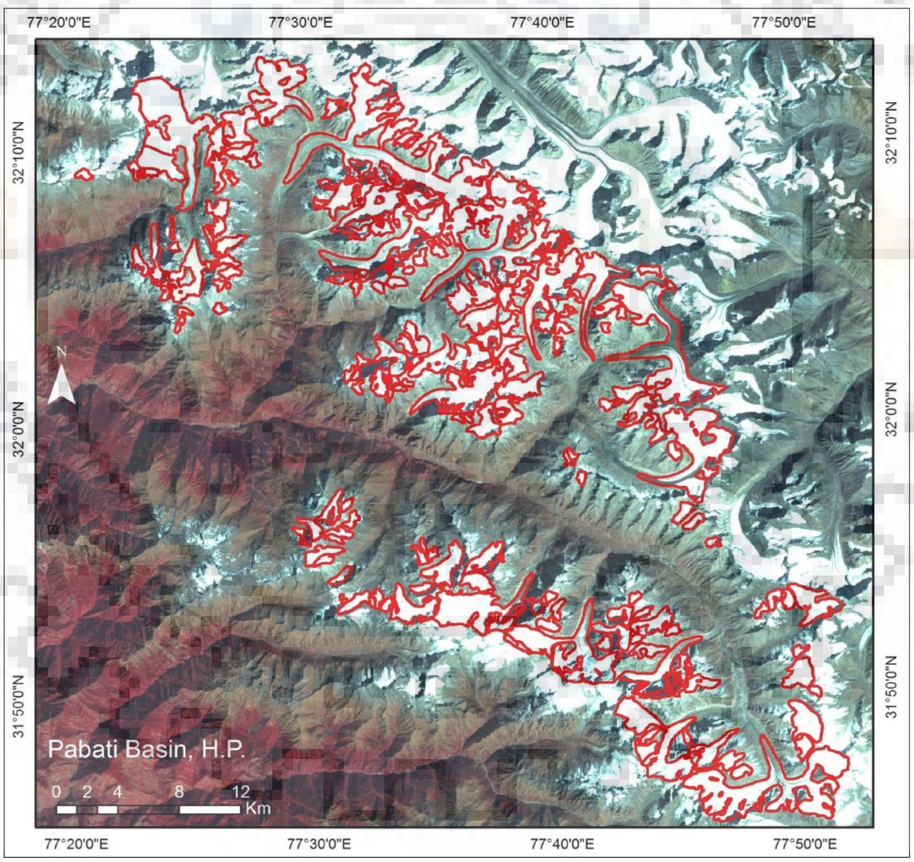


Figure 3.1: Map showing the study area, Parbati basin in Himachal Pradesh

3.3 Data Used

The following data have been used for the purpose of modeling the ice thickness distribution of the glaciers:

1. Landsat Thematic Mapper (TM) and Enhanced TM Plus (ETM+) imagery were obtained from 2000 to 2016. Band 8 (panchromatic) is used for which the spatial resolution is 15 m. Imagery is obtained for the period September to October,i.e. at the end of the melting season (http://earthexplorer.usgs.gov/). Taking the data at the end of the ablation season is advisable so blurring due to cloud cover is ruled out.

2. ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) DEM(downloadable at http://reverb.echo.nasa.gov/reverb) was used for calculation of slope of the area.

3. Glacier boundary datafor all the glaciers in the Parbati Basin were obtained from **Randolph Glacier Inventory (RGI).**

3.4 Methodology

Several indirect techniques have been used in the past to estimate the amount of glacier stored water, including the inference of mean depth from surface characteristics like surface area, empirical relations between volume and surface area or length or both, machine learning methods like neural nework algorithms using calculations based on DEMs, calculation of average ice flux from surface velocities and mass balance, and calculation of ice thickness from apparent mass balance. Data linked to mass balance distribution is not readily available for a large number of glaciers in the Himalaya. In this paper, therefore, ice thickness distribution over all glaciers in the Parbati basin is calculated using surface velocity data, slope and ice flow mechanics. The surface velocities are calculated using remote sensing techniques (Leprince and others, 2007).Gantayat et al. describe the laminar flow methodology for calculation of ice thickness distribution which is discussed here.

3.4.1 Estimation of surface velocity field

Sub-pixel corelation of satellite image data of consecutive years is used for obtaining the velocity vector fields at the surface of the glacier. The velocity vector field is obtained based on the displacement of images in both north-south and east-west direction. This co-registration of satellite images is formally done using a software called COSI-Corr (Co-registration of Optically Sensed Images), which is available for free and can be downloaded from the official website. Leprince et al. describe the set of algorithms and the underlying mathematical model in detail.

The window is slided for getting the best fit for the corelation. The software outputs 3 images after running the data and executing the algorithm: north-south displacement field, east-west displacement field and an SNR field that gives an assessment of the performance of the algorithm. Technically, every pixel that has a signal to noise ratio less than 0.9 and displacement greater than 85 m from the pixels linked to the same point in the base image is rejected. Using the two output images a velocity vector is produced for every pixel which is overlain on the base satellite image. All the resultant velocity vectors are then subsequently verified for their alignment and the magnitude of the displacement is then evaluated from the Eulerian norm of the images.

3.4.2 Calculation of depth

The laminar flow model method given by Cuffey and Paterson, 2010 is applied to estimate the depth distribution of glaciers based on surface characteristics, like surface velocity. The equation of the ice flow is given by:

$$U_s = U_b + \frac{2A}{n+1} \tau b^n H$$

Where, U_s and U_b are surface velocity and base velocity, respectively Since, there is no reliable information on the values of base velocity for glaciers in the Parbati basin, therefore base velocity is taken to be 25% of surface velocity, whose value is known from sub-pixel correlation of acquired satellite images with the aid of COSI-Corr software. Glen's flow law exponent is taken to be 3 . H gives the ice depth while A is a creep parameter, and its value is taken to be 3.24×10^{-24} $Pa^{-3}s^{-1}$. The value of the creep parameter depends on a number of factors like texture, grain size, sorting, as well as the amount of impurities present in the underlying or overlying layer.

The basal stress is given by:

$$\tau b = f \rho g H \sin \alpha$$

Here, ρ is the ice density which is nominally taken as 900 kg/m^3, g is the acceleration due to gravity and is 9.8 m/s^2. F is a scale factor which is the ratio between driving stress and basal stress along a glacier. For temperate glaciers, the scale factor is assumed to lie between 0.8 and 1. For the purpose of our study, f is taken as 0.8. For calculations of slope of the surface of glaciers at a given point location, ASTER Digital Elevation Model contours are used, which are at an interval of 100 m. Since the ice depth in the given locality is of the order of 10 m, this particular interval value being of greater order is apt for the objective of the study.

Equations (1) and (2) can be used to give the value of ice depth, H at a given point location which can give the thickness of the glacier between consecutive 100m elevation contours.

$$H=\sqrt[4]{\frac{1.5U_S}{Af^3(\rho g\sin\alpha)^3}}$$

The thickness values are then plotted to give an ice thickness distribution for all the glaciers in the Parbati basin. Smoothening of the depth values is then done using a 3 by 3 kernel in order to get rid of any erroneous values in the thickness distribution raster.

3.3.2 Uncertainty Analysis

To quantify the uncertainty in the estimated thickness values, take logarithm on both sides of equation 3 and differentiate subsequently:

$$\frac{dH}{H}=0.25[\frac{dU_s}{U_s}-\frac{dA}{A}-3\frac{df}{f}-3\frac{d\rho}{\rho}-3\frac{d(\sin\alpha)}{(\sin\alpha)}]$$

3.4 Results

3.4.1 Velocity and thickness distribution

The results for the glacier numbered RGI50-14.16005 in the basin are documented as an illustration. The surface velocity distribution for this glacier is shown in Figure 3.3. As can be seen, the velocity reaches its maximum value in the upper east portion of the trunk section, where they have values in the range 46-80 m per annum (depicted in blue color). In the western part of the trunk as well as the lower reaches, surface velocities gradually assume lower values, i.e. less than approximately 15 m per annum (depicted in red color).

The ice thickness distribution for glacier RGI50-14.16005 is depicted in Figure 3.4. The depth values assume their highest value in the middlemost section of the trunk, where they lie in the range of approximately 181 to 250 m. The thickness values progressively decreases as one moves towards the outer reaches of the glacier trunk where they are roughly less than 60 m. The thickness values at the snout of the glacier are roughly in the range 0-60 m.

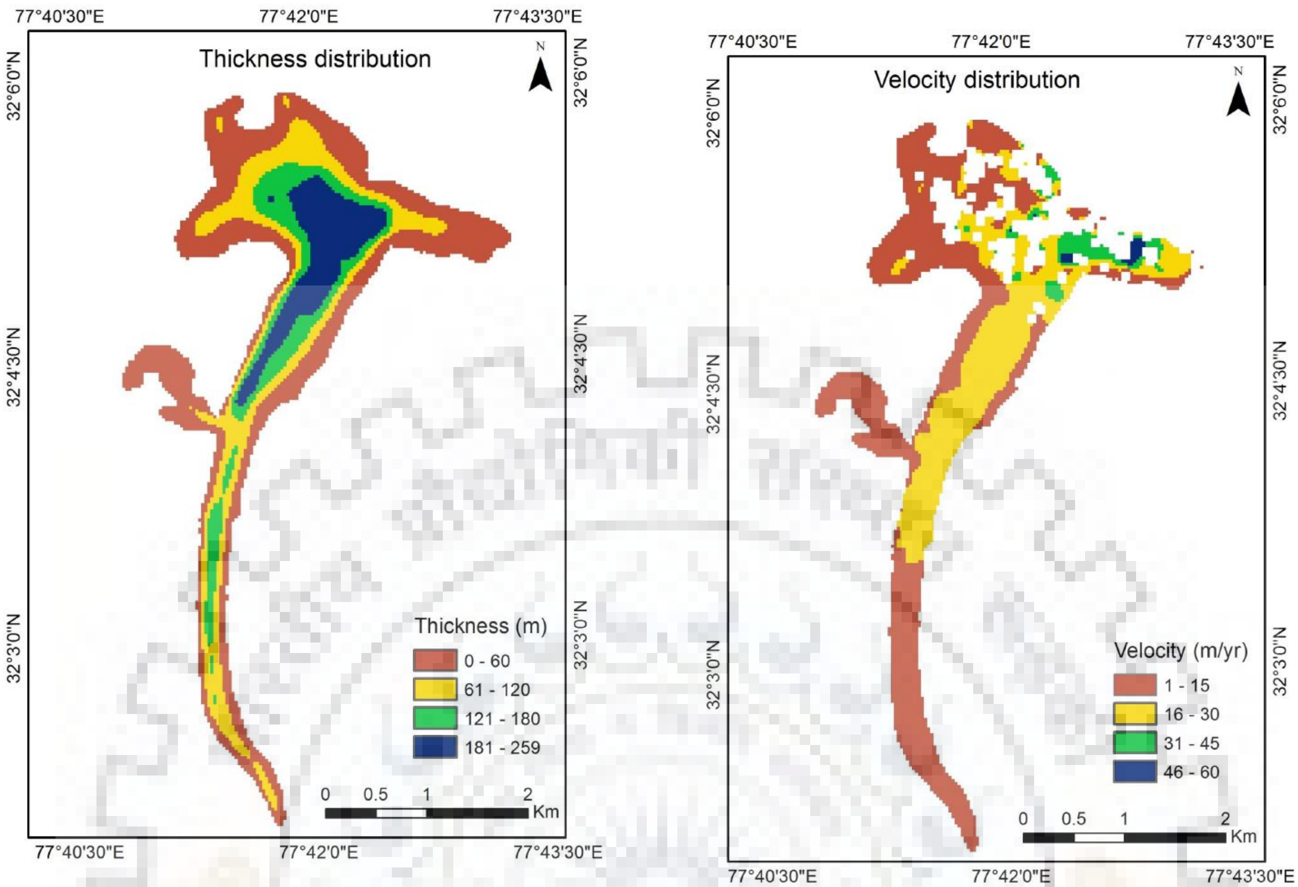


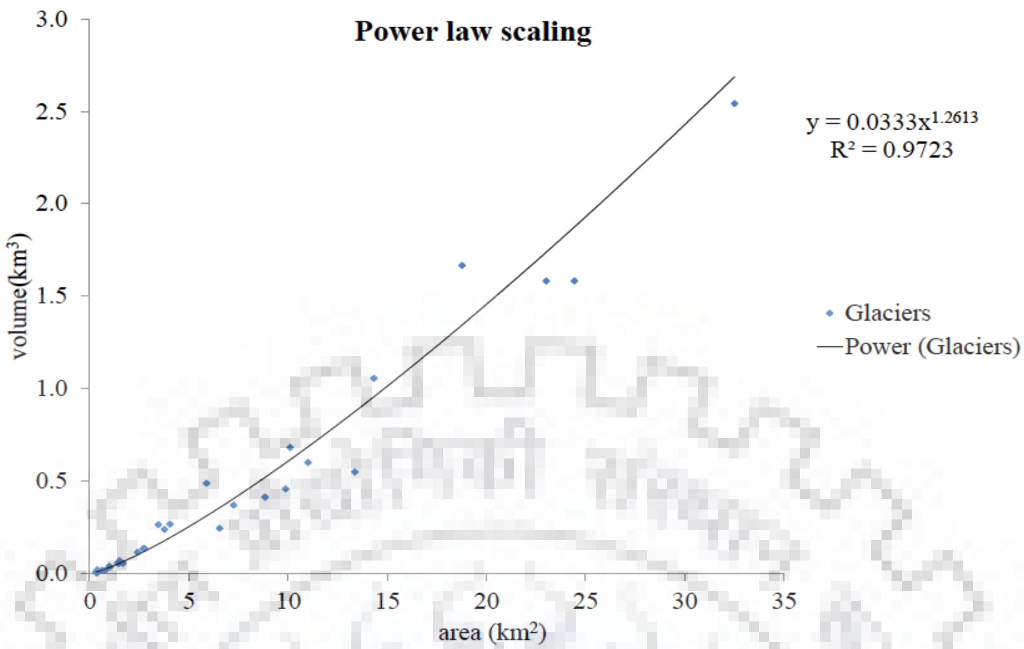
Figure 3.3 and 3.4: Thickness distribution of one of the glaciers in Parbati basin; Velocity distribution raster of the glacier

3.4.2 Volume-area scaling relationship

Bahr et al. gave the theoretical basis upon which a simple power law relation can be derived for the volume, V of any glacier with respect to its surface area, S. The empirical relation is based on a dimensionless exponent that depends on the type of glacier:
Van de Wal and Wild modified the relation with a scaling coefficient, sc, to model all the glaciers, where steady state is not applicable.

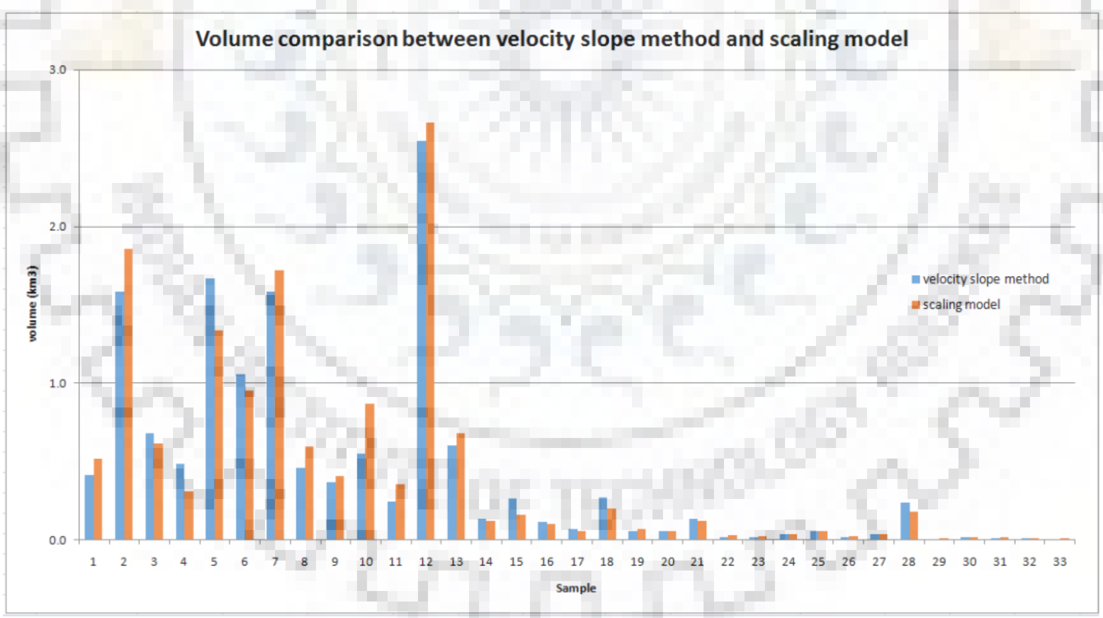
Volumes estimated for the 155 glaciers in Parbati Basin using the laminar flow methodology are plotted against their respective surface area on a log-log scale. Data for the surface area is collected from the Randolph Glacier Inventory. The V versus S plot (Figure 3.5) follows a straight line fit and its regression coefficient is found out to be 1.2136, i.e. $y=0.0333\,x^{1.2136}$.

The squared correlation coefficient is calculated to be 0.9723. The scaling coefficient assumes the value 1 when glaciers are in steady state. If not, the coefficient values need to be derived for each individual glacier. Otherwise, sc has to be derived for each individual



F

ig. 3.5: Scaling relationship (using power law) derived based on volume estimates from velocity slope method



glacier individually. If a glacier's initial surface area and ice volume are known, the value can be obtained empirically, as is done by Radic´ and Hock, 2007.

The volumes estimated using velocity slope method are then compared with volume calculated theoretically from the scaling model using power law, as is shown in Figure 3.5.

3.5 Conclusion

In this chapter, the ice thickness distribution for 155 glaciers in the Parbati basin is obtained using velocity slope method. The total glacier stored water of the 155 glaciers in Parbati basin, which covers an area of 377.16 km^2, is estimated as 21.07 km^3.

The regression coefficient obtained from the scaling relationship (using power law) derived based on the volume estimates from velocity slope method is 1.2136, and the squared correlation coefficient is calculated to be 0.9723.

These analyses show that the velocity slope method can potentially be used for assessing glacier volume and obtaining ice thickness distribution, where mass balance data is not available. For many Himalayan glacier, mass balance distribution data is not well documented, therefore, the velocity slope method can be conveniently applied to assess long-term health of Himalayan glaciers.

Chapter 4

Estimation of glacier stored ice in the Satluj and Beas basins of the Himalayas

Citation: Srinivasalu, P., Kulkarni, A., Godha, A., Goswami, A., Namboodiri, R., Shirsat, T., Krishnamurthy, N.,Jain, S., Bansiter, D., Momblanch, A., Holman, I., Ncube, S, Beevers, L., Snapir, B., Waine, T., Andrew O., Ojha, C., and Adeloye, A.: An estimate of glacier stored ice in the Satluj and Beas basins of the Himalaya, *European Geosciences Union 2018.* EGU2018-434.

ABSTRACT: The Satluj River originates near Manasarovar Lake and flows through Tibet, before entering India at Shipki La pass. The river flows west-southwest through the states of Himachal Pradesh and Punjab, where Beas river confluences with the Satluj river. Satluj river is fed by the glacier melt, snow melt and rain, and is considered to be the life line of Northern India, providing water for irrigation canals and a number of hydro-electric power projects like Bhakra-Nangal, Nathpa Jhakri, Kol dam and Baspa Hydel Project. The Satluj and Beas basins consist of 2018 and 469 glaciers with a glacierized areas of 1433 ± 71 km2 and 499 ± 25 km2 respectively. In the future, however, the glaciers in the basin are going be altered due to fluctuations in the climate. Basin scale assessment of the glacier volume in these reservoirs is crucial to assess the future changes in mass loss, melt runoff and hydro-electric potential. Hence in this study, the volume of glaciers in Satluj and Beas basins of the Himalaya are estimated using the automated laminar flow model and scaling equation.

The volume of the glaciers can be derived by using a laminar flow model with glacier surface velocity and slope derived from remote sensing images. Glacier surface velocities are obtained by sub-pixel correlation of consecutive year image scenes and slope is estimated from a digital elevation model at 100 m contour intervals. The thickness is initially obtained over multiple flowlines drawn on the glacier and then interpolated using thin plate spline interpolation over the entire extent of the glacier. The above process has been completely automated by using Python scripting. Currently this model is applicable to glaciers for which

uniform velocity fields are available. The thickness distribution of 298 glaciers are estimated by using the model in Satluj and Beas Basins, which cover an area of 588 ± 29 km2 and have an estimated volume of 27.5 ± 5 km3. However, large area of the basin is occupied by smaller glaciers and due to the presence of cloud cover, velocity field are not available for all glaciers. Hence, the volume of the other glaciers is computed by developing an empirical volume area scaling equation. A power law relation is derived between the area of the glaciers and volume estimates from the laminar flow model area and volume of the glacier, with scaling exponent λ = 1.2869. The total amount of glacier stored ice in Satluj and Beas basin is equal to 84 ± 15 Gt, obtained from modelled and statistically upscaled estimates of glacier volumes.

4.1 Introduction

The Himalayas extend over an area of around 40,000 km^2, and therefore constitute one of the largest ice bodies second to the Antarctic and Arctic regions (Bolch et al,, 2012). Himalayan glaciers have therefore been an area of great scientific interest. Many recent scientific studies indicate that the Himalayan glaciers are losing mass at different rates (Kulkarni et al., 2007; Venkatesh et al., 2012). For assessment of any future glacial retreat, an estimate of the current ice volume is the most important initial parameter. Many glacio-dynamical models also rely on ice volume as an initial parameter (e.g. Hubbard et al. 1998).

However, the lack of sufficient data especially about the amount of water stored in the different glaciers and their ice thickness distribution, poses significant difficulties in assessing Himalayan glaciers and their sustainability in the long run (Raina, 2009; Gantayat et al, 2014). There are huge differences in the estimates given on their rates of mass gain and mass balance distribution in scientific literature (Jacob et al., 2012). This severely reduces the feasibility of applying apparent mass balance methods for estimating volume, as have been done elsewhere, for example the Swiss Alps. Moreover, the uncertainties recorded in the characterization of glacier dynamics in the Himalayan and Karakoram region and some of the predictive models are of significant concern because these can have adverse consequences on water resources (Bolch et al, 2012).

In this chapter, an attempt has been made to estimate the total volume of glacier stored water in the Satluj and Beas basins using the velocity-slope method given by Gantayat et al., 2014. Thickness distribution is obtained for a total of 298 glaciers. The chief motivation is the lack of sufficient information on the most critical parameters for characterizing glacial dynamics, viz. glacier volume and surface velocity distribution in this basin. Field studies have been heavily restricted in the Himalayan-Karakoram region due to topographical constraints and irregular weather conditions. The volume of 155 glaciers in the basin is manually calculated using the method.

The estimated volumes are then used to derive an empirical relationship based on power law between volume and area. The physical basis for a scaling relationship between glacier volume and area or length is well documented (e.g. Bahr et al. 1997; Lliboutry, 1987). In fact, many earlier methods were based on statistically estimating the mean depth from surface area (e.g. Muller, 1970). Such empirical methods are essentially inversion models because unknown parameters, like mean depth can be estimated from available data. A lot of the documented work on glacial volumes in the Alpine glaciers is based on the power law behavior. For example, an estimate of the total volume of ice in the Swiss Alps is given by Muller et al. (1976) based on two different power law equations between glacier area and mean depth. The rule has been implemented for a number of Himalayan glaciers. However, the stability of the solutions given by these scaling models has been under scrutiny because these can be very sensitive to non-uniformity in the specified glacier boundary data, making the solution very inconsistent (Bahr et al. 2013).

3.2 Study Area

This study concerns glaciers in the Satluj and Beas basins in the Himalayas.The Satluj River originates near Manasarovar Lake and flows through Tibet, before entering India at Shipki La pass. The river flows west-southwest through the states of Himachal Pradesh and Punjab, where Beas river confluences with the Satluj river. Satluj river is fed by the glacier melt, snow melt and rain, and is considered to be the life line of Northern India, providing water for irrigation canals and a number of hydro-electric power projects like Bhakra-Nangal, NathpaJhakri, Kol dam and Baspa Hydel Project. The Satluj and Beas basins consist of 2018 and 469 glaciers respectively, of which 1202 glaciers lie in Tibet. The total basin area is 104048 km^2 of which the glacierized areas are 1433 ± 71 km2 and 499 ± 25 km2 respectively. The mean elevation of the glaciated region is 5395 m.

3.3 Data Used

The following data have been used for the purpose of modeling the ice thickness distribution of the glaciers:

1. **Landsat Thematic Mapper (TM) and Enhanced TM Plus (ETM+) imagery** were obtained from 2000 to 2016. Band 8 (panchromatic) is used for which the spatial resolution is 15 m. Imagery is obtained for the period September to October, i.e. at the

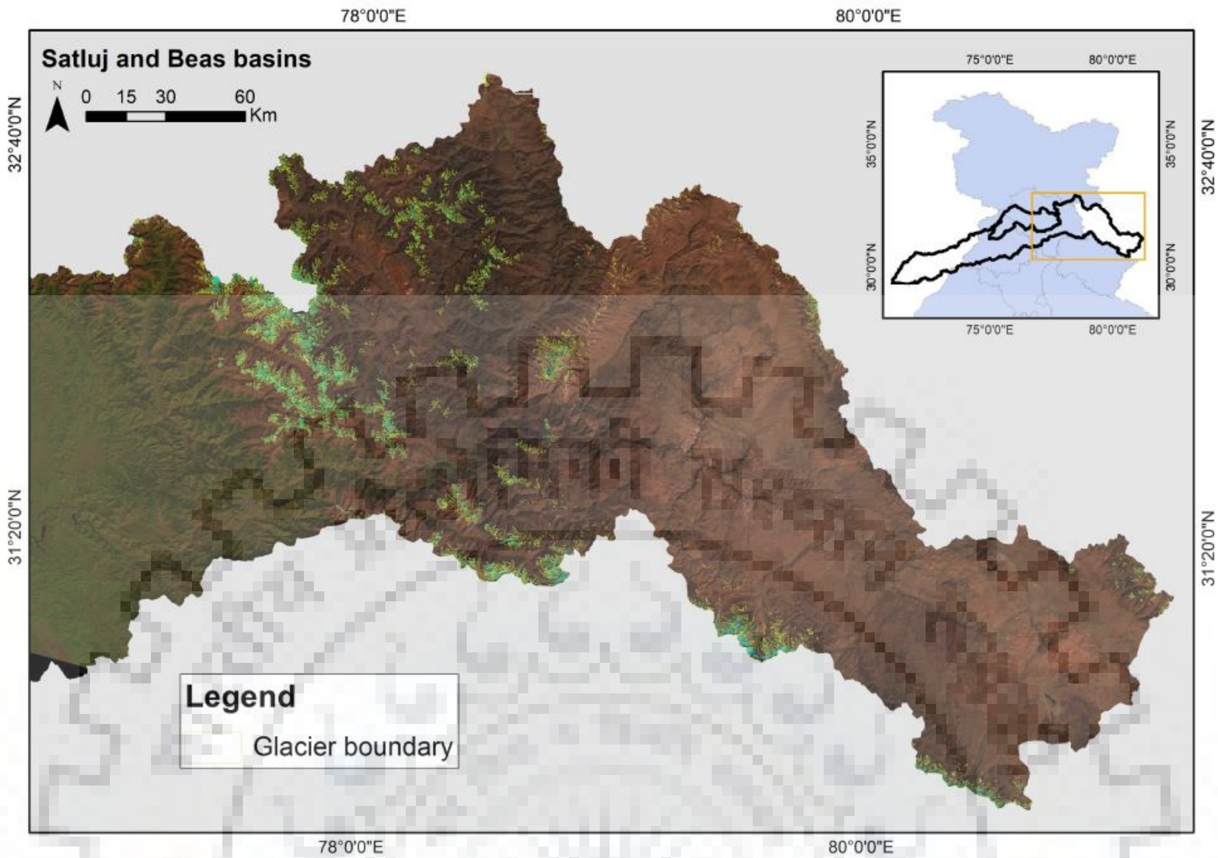


Figure 4.1: Map showing location of the glaciers in the study area, Satluj and Beas basins

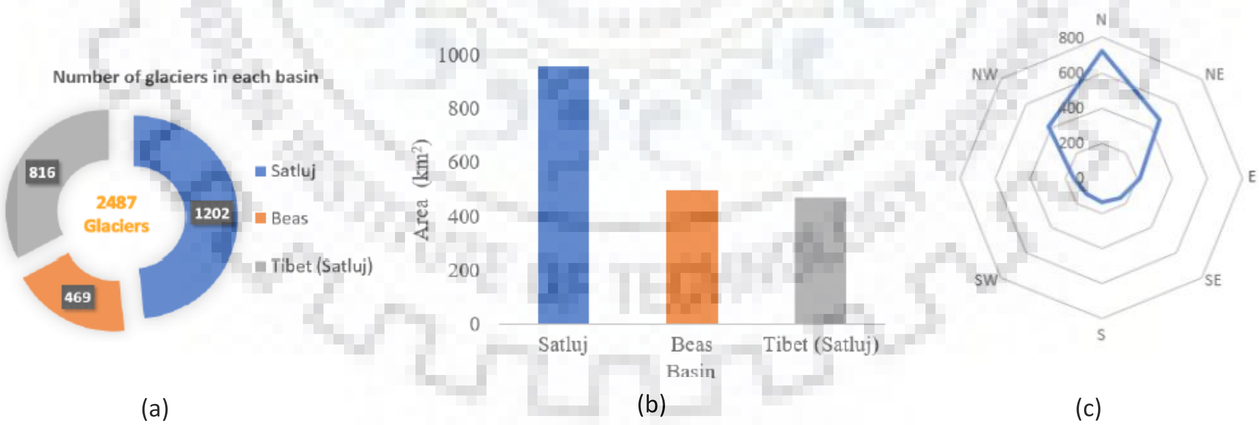


Figure 4.2 (a) Number of glaciers in each basin (b) Area of glaciated region in each basin (c) Aspect of glaciers in the study area

end of the melting season (http://earthexplorer.usgs.gov/). Taking the data at the end of the ablation season is advisable so blurring due to cloud cover is ruled out.

2. ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) DEM(downloadable at http://reverb.echo.nasa.gov/reverb) was used for calculation of slope of the area.

3. Glacier boundary data for all the glaciers in the Parbati Basin were obtained from **Randolph Glacier Inventory (RGI).**

3.4 Methodology

Several indirect techniques have been used in the past to estimate the amount of glacier stored water, including the inference of mean depth from surface characteristics like surface area, empirical relations between volume and surface area or length or both, machine learning methods like neural network algorithms using calculations based on DEMs, calculation of average ice flux from surface velocities and mass balance, and calculation of ice thickness from apparent mass balance. Data linked to mass balance distribution is not readily available for a large number of glaciers in the Himalaya. In this paper, therefore, ice thickness distribution over all glaciers in the Parbati basin is calculated using surface velocity data, slope and ice flow mechanics. The surface velocities are calculated using remote sensing techniques (Leprince and others, 2007). Gantayat et al. describe the laminar flow methodology for calculation of ice thickness distribution which is discussed here.

3.4.1 Estimation of surface velocity field

Sub-pixel corelation of satellite image data of consecutive years is used for obtaining the velocity vector fields at the surface of the glacier. The velocity vector field is obtained based on the displacement of images in both north-south and east-west direction. Thisco-registration of satellite images is formally done using a software called COSI-Corr (Co-registration of Optically Sensed Images), which is available for free and can be downloaded from the official website. Leprince et al. describe the set of algorithms and the underlying mathematical model in detail. The window is slided for getting the best fit for the corelation. The software outputs 3 images after running the data and executing the algorithm: north-south displacement field, east-west displacement field and an SNR field that gives an assessment of the performance of the algorithm. Technically, every pixel that has a signal to noise ratio less than 0.9 and displacement greater than 85 m from the pixels linked to the same point in the base image is rejected. Using the two output images a velocity vector is produced for every pixel which is overlain on the base satellite image. All the resultant velocity vectors are then subsequently verified for their alignment and the magnitude of the displacement is then evaluated from the Eulerian norm of the images.

3.4.2 Calculation of depth

The laminar flow model method given by Cuffey and Paterson, 2010 is applied to estimate the depth distribution of glaciers based on surface characteristics, like surface velocity. The equation of the ice flow is given by:

$$U_s = U_b + \frac{2A}{n+1} \tau b^n H$$

Where, U_s and U_b are surface velocity and base velocity, respectively Since, there is no reliable information on the values of base velocity for glaciers in the Parbati basin, therefore base velocity is taken to be 25% of surface velocity, whose value is known from sub-pixel correlation of acquired satellite images with the aid of COSI-Corr software. Glen's flow law exponent is taken to be 3 . H gives the ice depth while A is a creep parameter, and its value is taken to be 3.24×10^{-24} $Pa^{-3}s^{-1}$. The value of the creep parameter depends on a number of factors like texture, grain size, sorting, as well as the amount of impurities present in the underlying or overlying layer.
The basal stress is given by:

$$\tau b = f \rho g H \sin \alpha$$

Here, ρ is the ice density which is nominally taken as 900 kg/m^3, g is the acceleration due to gravity and is 9.8 m/s^2. F is a scale factor which is the ratio between driving stress and basal stress along a glacier. For temperate glaciers, the scale factor is assumed to lie between 0.8 and 1. For the purpose of our study, f is taken as 0.8. For calculations of slope of the surface of glaciers at a given point location, ASTER Digital Elevation Model contours are used, which are at an interval of 100 m. Since the ice depth in the given locality is of the order of 10 m, this particular interval value being of greater order is apt for the objective of the study.

Equations (1) and (2) can be used to give the value of ice depth, H at a given point location which can give the thickness of the glacier between consecutive 100m elevation contours.

$$H = \sqrt[4]{\frac{1.5 U_S}{A f^3 (\rho g \sin \alpha)^3}}$$

The thickness values are then plotted to give an ice thickness distribution for all the glaciers in the Parbati basin. Smoothening of the depth values is then done using a 3 by 3 kernel in order to get rid of any erroneous values in the thickness distribution raster.

3.3.2 Uncertainty Analysis

To quantify the uncertainty in the estimated thickness values, take logarithm on both sides of equation 3 and differentiate subsequently:

3.4 Results

3.4.1 Velocity and thickness distribution

The results for one of the glaciers in the basin are documented as an illustration. The surface velocity distribution for this glacier is shown in Figure 3.4. As can be seen, the velocity reaches its maximum value in the upper east portion of the trunk section, where they have values in the range 46-60 m per annum (depicted in blue color). In the western part of the trunk as well as the lower reaches, surface velocities gradually assume lower values, i.e. less than approximately 15 m per annum (depicted in red color).

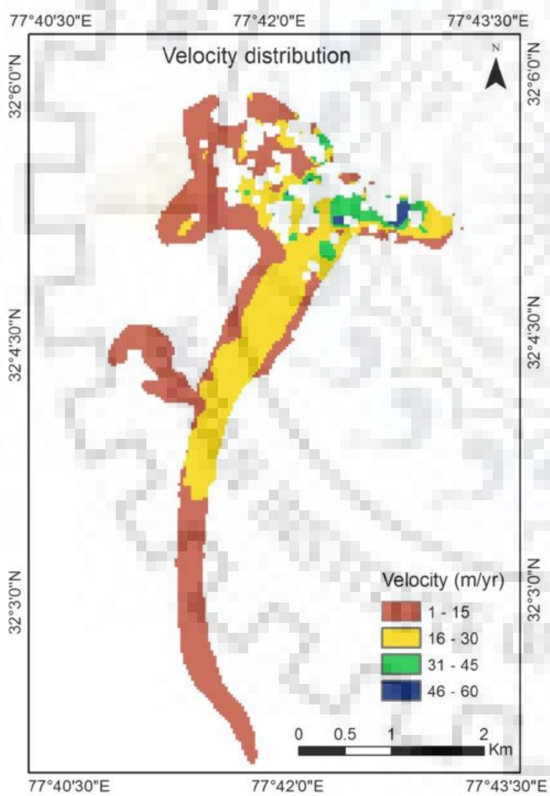


Figure 4.3: Surface velocity distribution of one of the glaciers

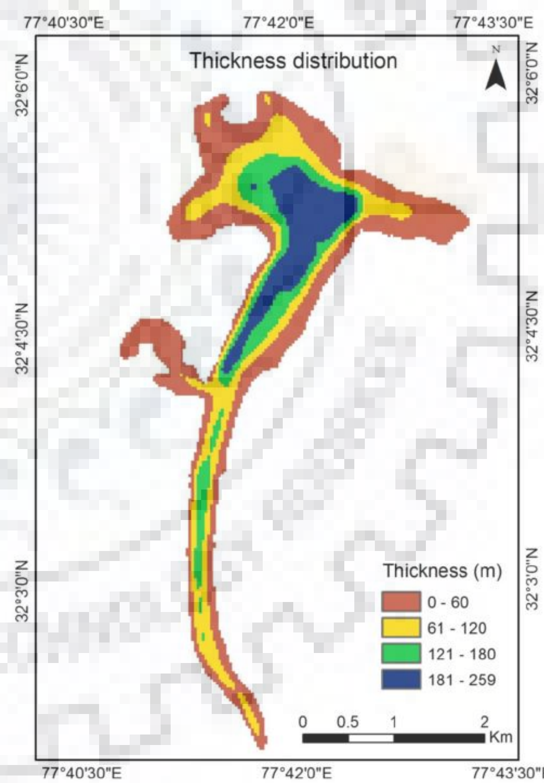


Figure 4.4: Thickness distribution of one of the glaciers

ice thickness distribution for this glacier is depicted in Figure 3.4. The depth values assume their highest value in the middlemost section of the trunk, where they lie in the range of approximately 181 to 260 m. The thickness values progressively decreases as one moves towards the outer reaches of the glacier trunk where they are roughly less than 60 m. The thickness values at the snout of the glacier are roughly in the range 0-60 m.

3.4.2 Volume-area scaling relationship

Bahr et al. gave the theoretical basis upon which a simple power law relation can be derived for the volume, V of any glacier with respect to its surface area, S. The empirical relation is based on a dimensionless exponent that depends on the type of glacier:

Van de Wal and Wild modified the relation with a scaling coefficient, sc, to model all the glaciers, where steady state is not applicable.

$$V = sc * A^X$$

The scaling coefficient assumes the value 1 when glaciers are in steady state. If not, the coefficient values need to be derived for each individual glacier. Otherwise, sc has to be derived for each individual glacier individually. If a glacier's initial surface area and ice volume are known, the value can be obtained empirically, as is done by Radic′ and Hock, 2007.

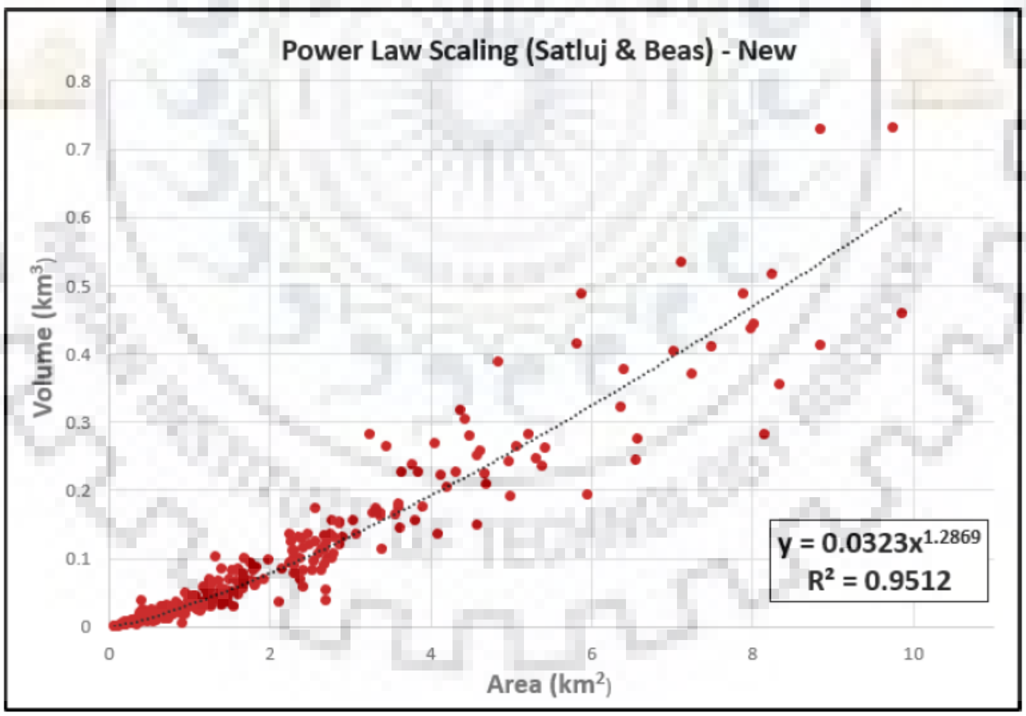


Figure 4.5 Power law behavior between volume derived from the model and area

A scaling equation is derived for empirically estimating the volume of other glaciers. Volumes estimated for the 298 glaciers in the Satluj and Beas Basins using the laminar flow methodology are plotted against their respective surface area on a log-log scale. Data for the surface area is collected from the Randolph Glacier Inventory. The V versus S plot (Figure 3.6) follows a straight line fit and its regression coefficient is found out to be 1.2869, i.e. $\mathbf{y = 0.0323\ x^{1.2869}}$. The squared correlation coefficient is calculated to be **0.9512**.

A spatial distribution of the ice stored in each glacier including the Tibet region is shown in Figure 4.6. Figure 4.7 depicts the amount of ice stored in each basin and the total mass of ice in Satluj and Beas basin.

3.5 Conclusion

In this chapter, the ice thickness distribution for 298 glaciers in the Satluj and Beas basin is obtained using laminar flow method. The total volume of 298 glaciers in Parbati basin, which covers an area of 1932 ± 96 km², is estimated as **27.5 ± 5 km³.**

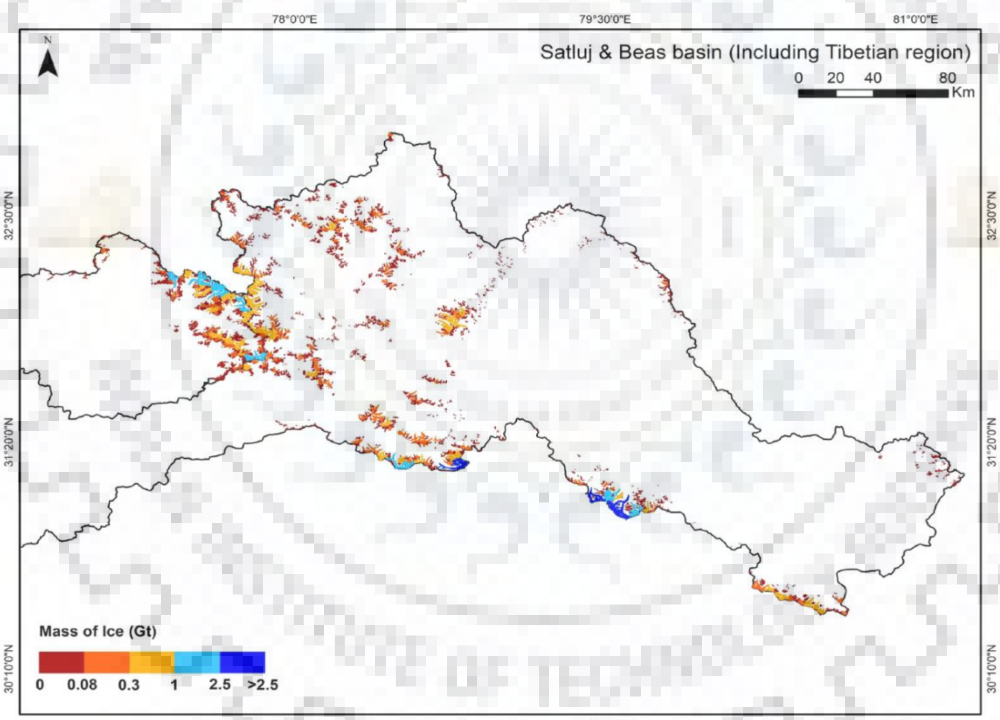


Figure 4.6. Map showing a distribution mass of ice in the Satluj and Beas basins

The regression coefficient obtained from the scaling relationship (using power law) derived based on the volume estimates from velocity slope method is 1.2869, and the squared correlation coefficient is calculated to be 0.9512.

These analyses show that the velocity slope method can potentially be used for assessing glacier volume and obtaining ice thickness distribution, where mass balance data is not

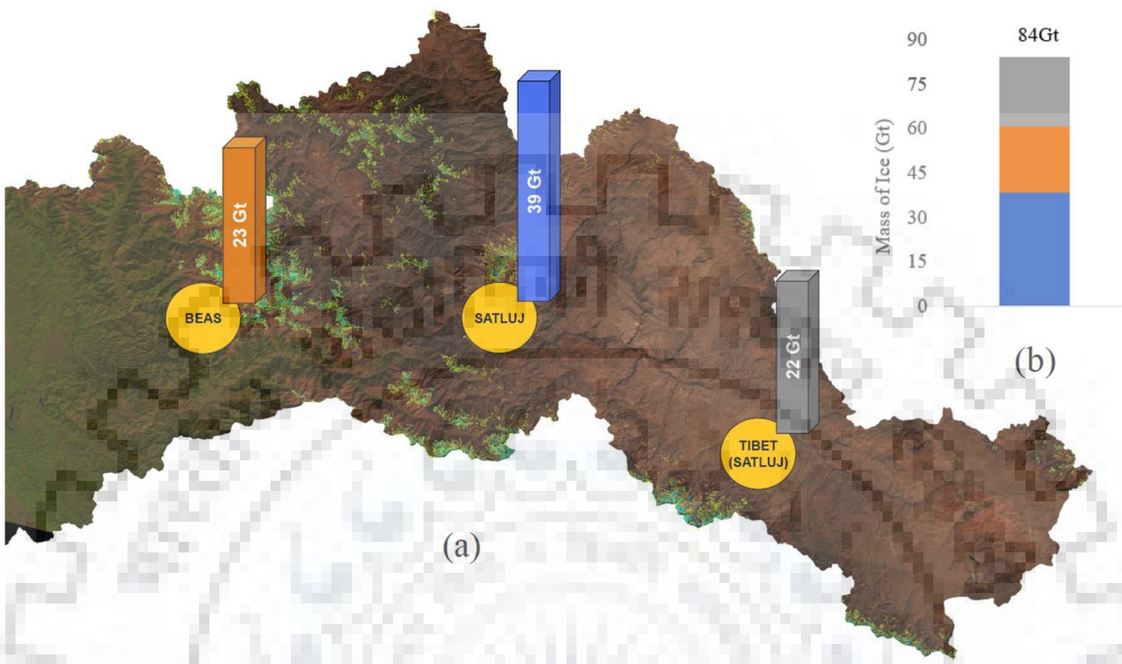


Figure: 4.7: ; Total mass of ice in Satluj and Beas basins

available. For many Himalayan glaciers, mass balance distribution data is not well documented, therefore, the velocity slope method can be conveniently applied to assess long-term health of Himalayan glaciers.

Acknowledgements

This study was funded by the Ministry of Earth Sciences under the Government of India.

PART B

MONITORING CHANGES IN GLACIAL LAKES

Chapter 5

A brief overview of Glacial Lake Outburst Floods in the Indian Himalayas

5.1 Introduction

Glaciers can potentially be a source for many hazards in the Himalayas, especially in lieu of their widely reported retreat as a response to climate change. Alongside such retreat processes, there is a huge reported increase in the number of potentially dangerous moraine dammed glacial lakes in the Himalayas. Such lakes can form from melting in the ice body enclosed by moraine deposits, both lateral and end, and through various other mechanisms, and have a huge potential to burst disastrously. There have been evidences of discharge rates as high as 30,200 m3/s and run-out distance greater than around 350m in case of such outburst floods. However, even with the prospects of such risks, mitigation of such glacial lakes is feasible (Richardsaon and Reynolds, 2000).

Scientific investigations marked a GLOF event about 450 years in Seti Khola in Nepal. In the year 1941, around 4,500 people lost their lives in an outburst flood in the Huaraz, Peru (ICIMOD 2010). The GLOF that occurred in 1964 in China damaged several kilometres of highway and 12 trucks of timber washed away. A number of GLOFs have been recorded in the Hindu Kush-Himalayas in the recent past. The most notable GLOF events occurred in 1985 in the Dig Tsho lake in Bhote Kosi in Nepal (ICIMOD 1993). Recent flash floods in Kedarnath, Uttarakhand is the most notable and devastating event in the history of India till date. The collected field data and scientific information available reports consecutive occurrence of these events on successive days causing heavy devastation in the Kedarnath area of Mandakini River basin. On 10thof June 2000 in Arunachal Pradesh, an outburst flood from a moraine dam extended up to 500 km downstream in the North-Eastern part of India, resulting in heavy damages. On June 2005, an outburst of a moraine dammed lake on Parechu river in China caused a trans-boundary flood event in Himachal Pradesh, India. On 16th June 2013, heavy rainfall followed by active erosion resulting sediment and excessive water.

Glacial lake outburst floods when the dam containing a glacial lake fails. The Inventory of Glacial Lakes defines a glacial lake as:

> A glacial lake is defined as a water mass existing in a sufficient amount and extending with a free surface in, under, beside and/or in front of a glacier and originated by glacier activities and/or retreating processes of a glacier.

The World Wide Fund in 2005 defines a glacial lake as:

> A glacier lake present above 3500m (msl) is considered to be evolved by retreat of glacier and classified as glacial lakes.

Many glacier lakes are observed at a height of around 3000 to 5000m above sea level. Glacial lakes most commonly form at such elevations because of retreat of valley glaciers in such regions. Retreat of glaciers has fairly grown in the recent decades (Kulkarni et al. 2000), owing to increasing rates of snow and ice melting caused by a rapid increase in global warming, especially in the latter half of the 20th century. Glacial lakes are classified as follows:

Moraine-dammed glacial lakes: These lakes are formed when glacier ice enclosed by lateral and end moraines on its sides melts during a long-term glacier retreat phenomenon. Small interconnecting lakes may coalesce to form a larger lake and expand even more. They are further classified as:

- End moraine dammed lake
- Lateral moraine-dammed lake (ice free)
- Lateral moraine-dammed lake (with ice)

Iice-cored moraine and an ice-free moraine are described by ICIMOD as follows. Before the ice body of the glacier completely melts away, glacier ice exists in the moraine and beneath the lake bottom. The ice bodies cored in the moraine and beneath the lake are sometimes called dead ice or fossil ice. As glacier ice continues to melt, the lake becomes deeper and wider. Finally when ice contained in the moraines and beneath the lake completely melts away, the container of lake water consists of only the bedrock and the moraines.

Ice-dammed glacial lakes: These lakes form when a tributary or a bunch of tributaries flowing into a glacier valley are intercepted by an advancing glacier mass, causing lake formation on one of the sides of that glacier. They are further classified as:

- Supra glacial lakes
- Glacier ice dammed lakes

Supraglacial lakes form within a glacier body a few meters away from lateral or end moraines and typically have a diameter of up to a hundred meter, mostly about half of the width of the valley in which it lies. They are characterized by frequent displacing, coalescing or poring.

Erosion Lakes: An erosion lake forms after the retreating process of a glacier when a small body of glacier ice melted in a depression is flanked by glacier mass. It is generally common to find such lakes in a cirque valley or a trough valley-type glaciers.

5.2 Glacial Lake Outburst Floods (GlOFs)

A glacial lake outburst flood is a type of outburst flood which occurs when the dam containing a glacial lake fails. It refers to rapid discharge of water charged with debris due to force from a glacier. Such outburst floods can wreath havoc in the downstream region and can cause severe loss of lives and property. Since the outburst flood can be heavily fuelled with debris, they have the capacity to potentially erode a settlement area on a massive scale.

GLOFs are caused by climate changes like global warming. Due to the rise in the mean temperature on Earth's surface, many glaciers are retreating at varying rates which can add to the amount of water stored in associated glacial lakes. The phenomenon of GLOF in most of the cases is triggered by ice or snow avalanche, rock fall or landslides, seepage of water through dam ice core melting, increased inflow of melt water leading to expansion of lakes and earthquakes.

As such, the outburst can be caused by one of the following mechanical failures: failure of an enclosed water body, gradual expansion of lakes or internal tributaries or any other channel or a catastrophic glacier failure that can result in the discharge of the enclosed water to the outer reaches of the glacier trunk.

5.3 Glacial lakes and GLOFs in Himalayas

The Himalayan and Karakoram regions extend over a surface area of around 40,000km2 and therefore constitute one of the largest ice bodies second to the Arctic and Antarctic regions. Therefore, studying Glacial Lake Outburst Floods in the Himalayan context is of utmost importance.

The Indian Himalayas have a glaciated cover of about 23, 300 square km (Philip and Sah, 2004). The traverse the upper northern band spanning from the states of jammu and

Kashmir in the west to Assam and Arunachal Pradesh in the east. Indian Himalayas have more than 270 glacial lakes that have a size greater than 1 square kilometer.

Several studies on the melting of glaciers in the Indian Himalayas give an indication of the most potentially hazardous glaciers in the region. The Siachen glacier is melting at the rate 31.5 m/year, followed by Bara Shigri and Pindari glacier (Mool, P.K. et al. 2001b). In terms of length, Parbati glacier has shown a very high retreat to about 6800m from the year 1963. The following figure shows the retreat of Gangotri glacier snout in the past 220 years.

Glacial lakes in the Indian Himalayas are the highest in number in the state of Jammu and Kashmir, followed by Sikkim and Himachal Pradesh, in turn followed by Uttarakhand and Arunachal Pradesh. Many recent studies show the increase in number of lakes in the Indian Himalayas.

5.4 Relevance of Remote Sensing and GIS Techniques

Since Himalayan glaciers have their snow line above 3800 meters from the m.s.l (Hewitt, 2011), geological study of glaciers in this region like monitoring and inventory preparation requires extensive time and resources

With the help of space-borne technologies like Remote Sensing and Geographic Information System, it is possible to monitor, map and perform in-depth analysis of these high altitude lakes with reasonable accuracy. With the help of products like Digital Elevation Model (DEM) and satellite imageries, it is easy to extract critical information like surface feature, geometry, slope, elevation and perform time series analysis. Hence, remote sensing acts as an important tool for qualitative and quantitative hazard assessment of glacial lakes. Using GIS, huge amount of geographic information can be stored and retrieved in database that can be used for further analysis and simulation purposes (Aggarwal ,2012).

Chapter 6

Methods to assess glacial lake hazards using Remote Sensing & GIS techniques: A review

6.1 Introduction

Several researchers have mapped glaciers and glacial lakes throughout the Himalayan cryosphere (Kulkarni et al., K. Babu et al.). K. Babu et al. mapped glacial lakes in the state of Uttarakhand using high resolution CORONA, Hexagon and LISS IV data. A total of 362 lakes were identified in the entire state which include supraglacial, proglacial, erosional, and blocked lakes. The glacial lakes mapped in recent studies mainly include proglacial/moraine dammed lakes as their growth is the prime signature of glacial retreat. Most northern states in India that have high density of glacial lakes like Jammu and Kashmir, Himachal Pradesh, Sikkim, Uttarakhand etc have a very well developed river network with the major rivers being Yamuna and Ganga. ASTER DEM 30m can be potentially used to delineate the major basins and their respective sub-basins using drainage network analysis. Contours at regular intervals can be created using ASTER DEM to extract AOI above 3500m above mean sea level.

Identification of lakes essentially requires a visual interpretation of satellite data. Visual interpretation for the efficient identification of the lakes is done using rectified CORONA datasets or LANDSAT 5, 7, 8 or Sentinel data. The geometry of the lakes is usually obtained for multiple years at intervals over a significant time period so as to perform a time series analysis of the spatial extent of glacial lakes. The identified lakes then need to be categorized for better assessment of the region. Proglacial lakes, cirque lakes etc can technically differ in the way they expand or in terms of their overall stability. For example, many erosional lakes have been observed to be stable in the past. Identification or delineation of lakes is followed by mapping of the lakes at a chosen scale to create an inventory of lakes. The detailed procedure of the methodology is given in the figure 3.

6.2 Data Preparation

Selection of proper dataset is of prime importance in any scientific study. During summer, the Indian Himalayas acquire maximum rainfall and most of the area remains clouded. Thus, availability of cloud free images and images without snow-cover is almost impossible for the region. Therefore, satellite imageries of LANDSAT and CORONA with maximum 10 percent cloud cover and a minimum snow cover between September and December should be chosen for the study. The ASTER GDEM version 2 data is a good choice for altitude and slope calculation. Layer stacking of different bands of image, image mosaicking, band combination and pan sharpening can be done using softwares like ERDAS Imagine and ArcGis 10.1 or other open source software like GRASS GIS, QGIS etc to prepare the data for further processing. This is generally followed by extensive use of parameters commonly used in the scientific study of glacial lakes like Normalized Difference Water Index (NDWI) (Huggel et al., 2002) or Normalized Difference Snow Index (NDSI) (Paul et al., 20102) for all data sets for cross verification. This is discussed at length in the methodology section of this chapter.

6.2.1 Satellite Data

Freely available high resolution satellite imagery and Digital Elevation Model (DEM) acquired from USGS Earth Explorer can be utilized for the purpose of glacial lakes mapping. LANDSAT is available from 1972 and CORONA data is obtainable from 1965, and can be used to carry out the time series analysis of glacial lakes for the years after these. Since the area is mostly cloud covered, care must be taken to choose similar season datasets between September to December to avoid the cloud cover ensuring least snow coverage (Jain et al. 2012).

Table 6.1 lists satellite datasets and their respective specifications.

(a) CORONA

Corona is an American reconnaissance satellite launched in June 1959 by the U.S Air Force for military purposes. Corona images can be used to map the lake especially as an initial reference data, since these imagery dataset is obtainable from 1968. Specifications are outlined in the table.

(b) LANDSAT

LANDSAT 1 is based on 23 Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS) with new spectral bands, a deep blue coastal / aerosol band and a shortwave-infrared cirrus band, for accurate measurement of water quality and improved detection of high, thin clouds. LANDSAT 2 is identical to its predecessor. LANDSAT 3 includes a fifth thermal band along with the four other bands used in MSS (green, red, infrared). LANDSAT 4 has a new sensor incorporated along with MSS, known as the Thematic Mapper (TM).

DATA	BANDS	RADIOMETRIC RESOLUTION	SPATIAL RESOLUTION	SWATH WIDTH
TM	1,2,3,4,5,7	8 bit	30m	185 kms
	6	8 bit	120m	185 kms
ETM+	1,2,3,4,5,7	8 bit	30m	185 kms
	6-1,6-2	8 bit	60m	185 kms
	8	8 bit	15m	185 kms
OLI /TIRS	1,2,3,4,5,6,7	8 bit	30m	185 kms
	8	8 bit	15m	185 kms
	10,11	8 bit	100m	185 kms
CORONA /KH4			4m	

Table 6.1. Satellite dataset specification for Landsat and CORONA

This sensor has enhanced features of improved spectral and spatial resolutions with seven spectral bands (blue, green, red, near-infrared, mid-infrared and thermal).

LANDSAT 7, launched in 1999, provides most accurately calibrated satellite for earth-observing purposes. LANDSAT ETM+ replicates the features of TM along with newly added enhanced features. LANDSAT 8, launched in 2013, contains two sensor pay-load, the Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS) with new spectral bands, a deep blue coastal/ aerosol band and a shortwave- infrared cirrus band, for accurate measurement of water quality and improve detection of high, thin clouds.

LANDSAT mission has been successful in providing 44 years of multispectral data of the Earth's surface since 1972. Therefore, it can prove of high importance in assessing glacial hazards.

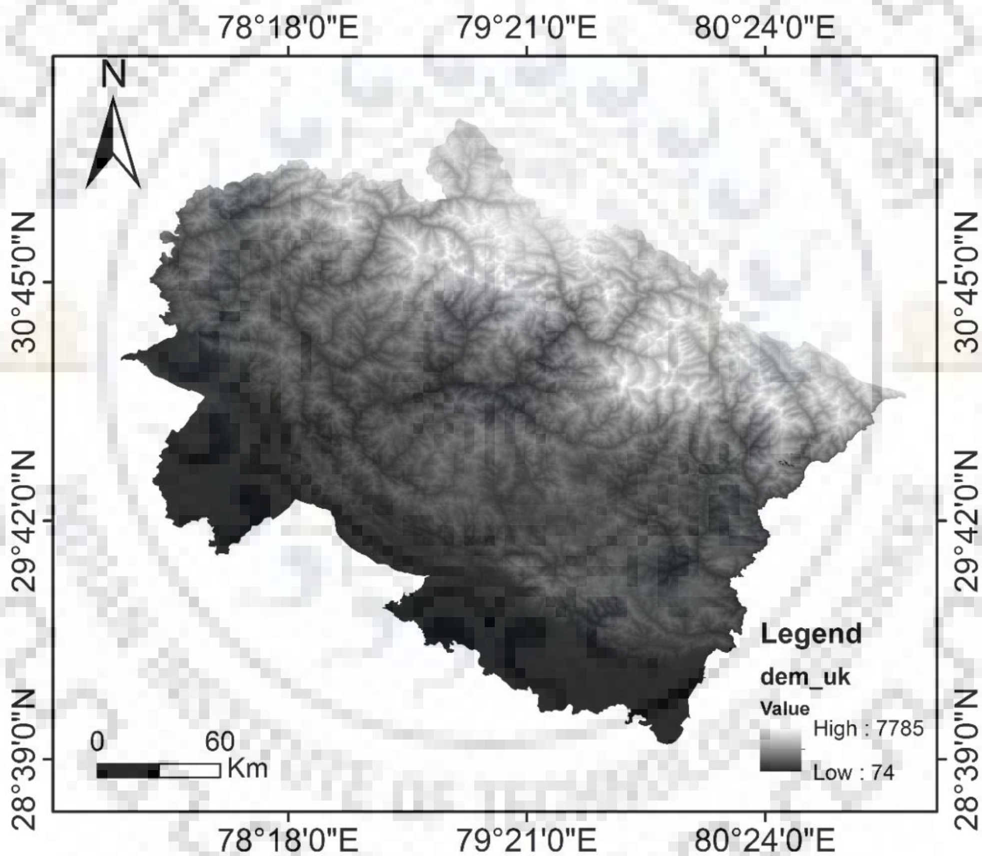


Figure 6.1. An illustration of ASTER Digital Elevation Model data for the Uttarakhand region (Ketan et al., 2017)

(c) ASTER DEM (Digital Elevation Model)

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) (launched in 1999) is an imaging instrument with an altimeter that maps the Earth terrains at very high spatial resolutions. The sensor provides Digital Elevation Model (DEM) of Earth's surface between 83°S and 83°N and is composed of 22,600 1°-by-1° tiles. The acquired data is available in GeoTiff format with geographic lat/long as coordinate system, WGS84/EGM96 as geoid and grid size of 1 arc-second i.e. 30 m (Figure 6.1).

For glacial lakes identification, a high quality DEM is required for calculating important parameters like maximum, minimum and mean elevation and slopes. ASTER DEM data is extremely useful in glacier-related studies due to its high positional accuracy in mountainous terrains in comparison to SRTM.

6.2.2 Software

GIS platforms like ArcGIS 10.1 are nonetheless relevant for any study pertaining to hazard assessment of glaciers or glacial lakes. ERDAS IMAGINE 15 supplies all tools for remote sensing, GIS and photogrammetric needs. ENVI 4.5 also renders useful especially since all tools are accessible from ArcGIS toolbox.

6.3 Ortho-rectification of satellite dataset

Bhambri et al. 2011 have suggested that individual strips taken from USGS Earth Explorer or other platforms and all subsets be co-registered based on a two-step approach:

(1) application of a second order transformation based on ground-control points (GCPs) and the ASTER digital elevation model (DEM) using ArcGis 10.1; followed by
(2) a spline adjustment using ArcGIS 10.1.

Stable river junctions and mountain peaks can be used to collect GCPs assuming no changes occurred on the ground. For each Corona subset, 30–255 GCPs are generally acquired from Landsat OLI and ASTER imagery for co-registration. Special focus on the adjustment of the area around the glaciers and glacial lakes on Corona images in respect of Landsat and ASTER imagery is advisable for consistency of results during rectification of Corona imagery (Bhambri et al., 2011). To assess positional accuracy, a few common location points such as river junctions identified in both ASTER images and Corona subsets are used. Landsat ETM+ and OLI images can be co-registered, for example, with the ASTER DEM and ASTER imagery using the projective transformation algorithm.

6.4 Identification of glacial lakes

Remote Sensing techniques using space borne imagery is the most successful tool for assessment of glaciers and glacial lakes in the high mountainous terrains. Glacial lakes normally appear light bluish to black in colour when displayed in Standard False Colour Composition of remote sensing data (Huggel et al., 2002). Their shape varies from rounded to oval and some are irregular in outline exhibiting smooth texture as compared to surrounding rough texture of the mountain. They are often associated with glaciers at higher altitude and presence of river channels at lower heights. Lake existing above ~3500 m from the mean sea level only can be considered for mapping, using the literature information that snow line in Himalayas exists above 3800 m from msl. Many supervised and unsupervised classification methods have been carried out for mapping these features.

6.4.1 The NDSI approach (Paul et al., 2000)

Normalised Difference Snow Index (NDSI) image thresholding is proven to be most accurate and time efficient (Paul et al., 2000). It is mainly useful for extraction of ice and snow (Banerjee, 2013). But it lacks some accuracy like misclassification of shadow as lakes and misclassification of water bodies as snow.

6.4.2 The NDWI approach (Huggel et al., 2002)

NDWI or Normalized Difference Water Index proposed by Huggel et al. (2002) to classify the glacial lakes by taking the advantage of the low water reflectance in the NIR band and high reflectance in the blue band. It is a band rationing method. It utilizes the two region of electromagnetic radiation-blue (0.63-0.69µm) and the near infrared region (0.76-0.90µm). NDWI is calculated as given below

Equation 1: $NDWI = NIR - BNIR + B$

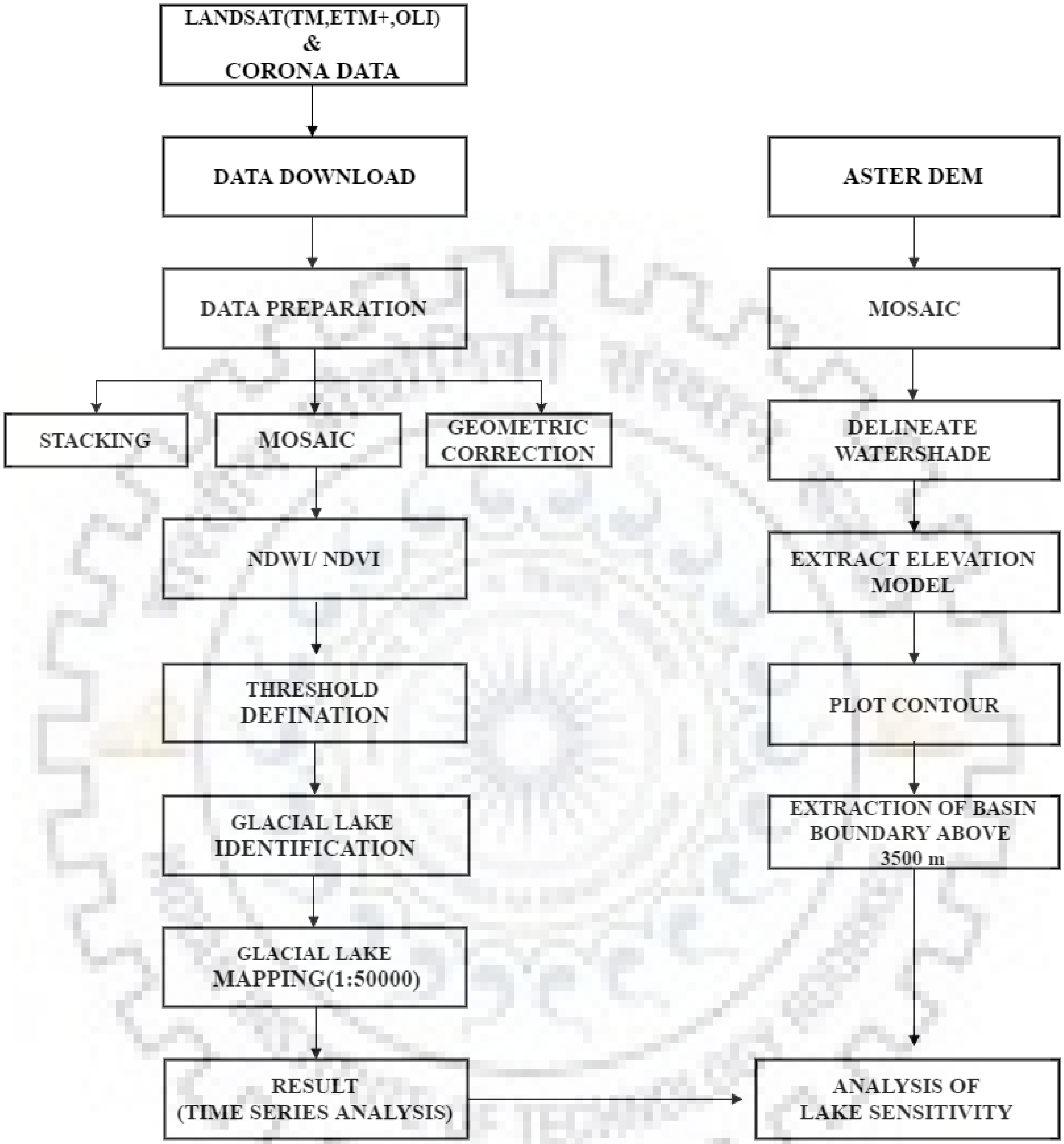


Figure 6.2. Workflow for delineation of glacial lakes (Source Bhambri et al. 2014)

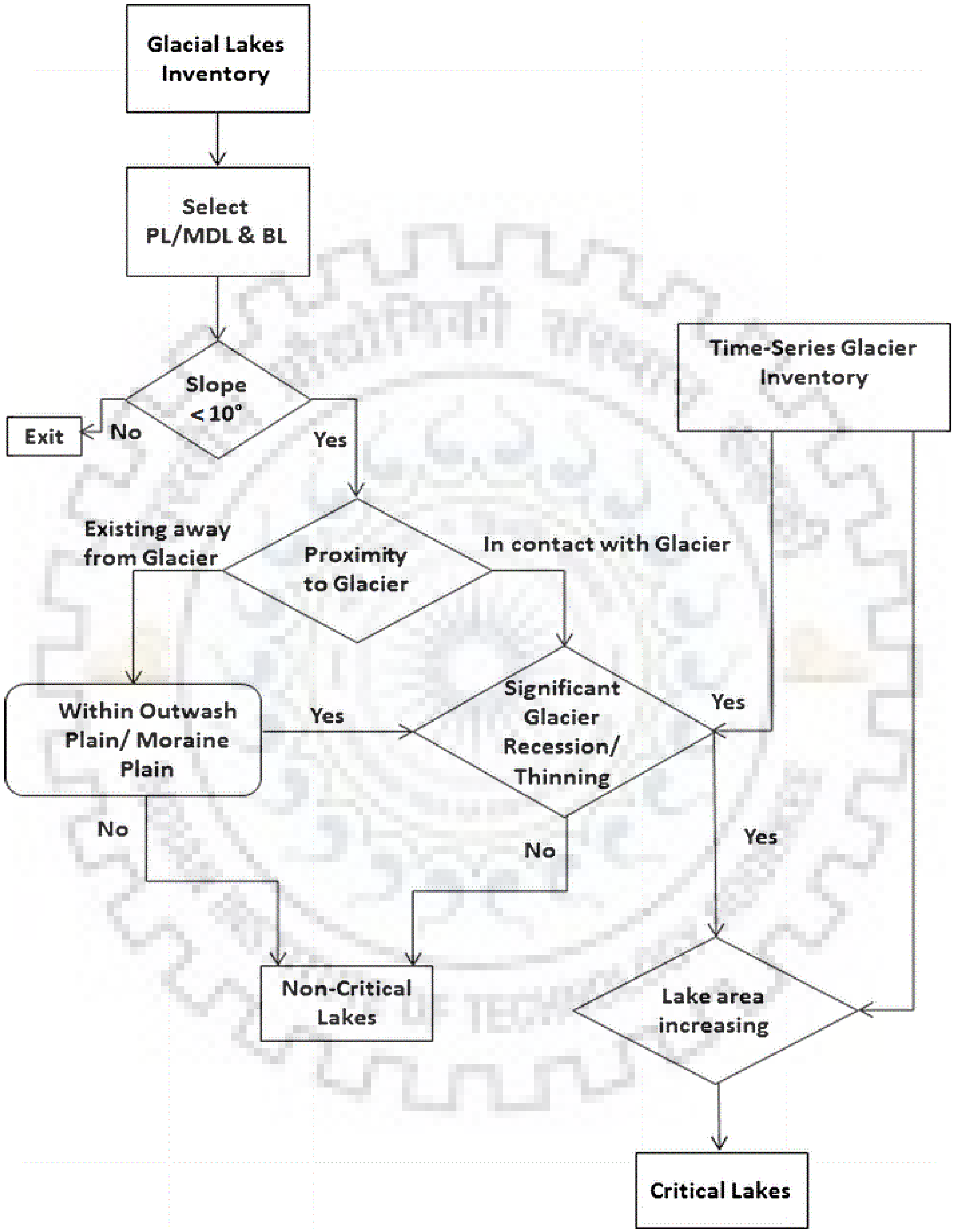


Figure 6.3. Workflow for hazard assessment of glacial lakes (Source Bhambri et al., 2014)

Where, NIR represent the DN values in Near Infrared region, B represent DN value in blue region and NDWI represent the DN value output. After the analysis of Satellite images, the following minimum and maximum values of NDWI was defined.

NDWI= 0.01 to 0.54

6.4.3 Sensitivity analysis of glacial lake delineation

Using the ASTER Global Digital Elevation Model (GDEM) study area can be divided into different elevation zones based on contour levels. (Bhambri et al., 2004) Total area and number of all mapped lakes in each elevation zone can be compared in all the data sets.

The elevation zone, where maximum changes in area and number of lakes is observed will be considered more sensitive for glacial lakes.

6.6 Hazard assessment of glacial lakes

Based on visual interpretation techniques, a simplified methodology can be applied to classify potentially hazardous glacial lakes from the current lake inventory. The first step is to select all the moraine-dammed lakes and blocked lakes and then to analyze the selected lakes through the slope map prepared from ASTER DEM. A slope value less than 10° can be filtered for lakes having moderate to steep slopes. The output lakes are processed with the criteria of proximity to the glacier. The lakes which are close to the glaciers are hazardous and more susceptible to breach of ice-core or moraine-dam and create GLOF. The recession history of the glacier from the time-series data sets (LANDSAT, CORONA) can thus be used for analyzing glacial lakes.

The recession of the glacier gives the area for the lakes to grow in larger dimensions. Most of the receding glaciers show significant growth of the PL/MDL. Finally if the lake area is increasing consistently, such lakes are considered to be dangerous. By applying this methodology for the glacial lakes, lakes which are potentially critical can be identified and taken for further on-site investigation and hazard assessment.

Several criteria are mentioned in the literature to identify the potential and hazardous lakes. R.J. Mckillop and J.J.Clague (2007) suggested eighteen major parameters for defining risk of Glacial Lake Outburst Floods. Bhambri et al. 2011 took the following few parameters for delineating the vulnerability criteria from remote sensing prospective.

1. Lake area Growth
2. Connectivity with the glacier
3. Slope of the lake
4. Distance of lake from basin outlet

PARAMETERS	CONDITION	CONCLUSION
Growth in lake area	If growth ≥100%	Lake is vulnerable
	If growth<100%	Lake is not vulnerable
Connectivity with Glacier	If distance≤500m	Lake is vulnerable
	If distance >500m	Lake is not vulnerable
Slope of the Lake	If slope ≤ 4	Lake is vulnerable
	If slope> 4	Lake is not vulnerable
Distance from the settlement	If distance ≤60,000m	Lake is vulnerable
	f distance> 60,000m	Lake is not vulnerable

Table 6.2: A set of threshold conditions for the parameters for assessment of lake vunerability

Table 6.2 summarizes a set of threshold conditions for the given parameters, and a conclusion regarding the vulnerability of a lake based on these parameters.

Chapter 7

Conclusions and Perspectives

In this thesis, an automated approach based on laminar flow of ice is used to estimate one variable of difficult access, especially in the Himalayan context, due to lack of sufficient data on mass balance distribution : ice thickness distribution or glacier volume. The volume of the glaciers was derived by using a laminar flow model with glacier surface velocity and slope derived from remote sensing images. Velocity slope methods were convenient, especially since velocity and slope data could be easily derived from available datasets (satellite imageries from USGS, ASTER DEM data, boundary data from Rundolph Glacier Inventory etc). Automating enabled calculation of glacier volumes in an efficient way, which otherwise would have required long and tedious pre-processing and manual execution for analysis. The accuracy of the model was qualitatively assessed based on existing measurements and a data validation approach was established.

Currently, this model is applicable to glaciers for which uniform velocity fields are available. The thickness distribution of 298 glaciers were estimated by using the model in Satluj and Beas Basins, which cover an area of 588 ± 29 km2 and were shown to have an estimated volume of 27.5 ± 5 km3. However, large area of the basin is occupied by smaller glaciers and due to the presence of cloud cover, velocity field are not available for all glaciers. Hence, the volume of the other glaciers was computed by developing an empirical volume area scaling equation.

The total glacier stored water of the 155 glaciers in Parbati basin, which covers an area of 377.16 km2, is estimated as 21.07 km3. The regression coefficient obtained from the scaling relationship (using power law) derived based on the volume estimates from velocity slope method is 1.2136, and the squared correlation coefficient is calculated to be 0.9723.

A power law relation was derived between the area of the glaciers and volume estimates from the laminar flow model, with scaling exponent λ = 1.2869. This enabled the estimation of the total amount of glacier stored ice in Satluj and Beas basin, which is equal to 84 ± 15 Gt, obtained from modelled and statistically upscaled estimates of glacier volumes.

For the purpose of establishing the scaling relationship, glacier areal extent could be conveniently obtained using remote sensing techniques and since numerous inventories are now providing reliable data. Earlier, depth measurements were difficult and generally obtained using scaling method. The scaling methods provided large errors in volume estimates in the Himalaya, due to limited availability of field data. This provided large uncertainties in the volume estimates. From this study, the application of the automated model and subsequent analysis show that the model can be conveniently and efficiently applied to a large number of basins, and can further be used to establish scaling relationships that are more accurate. However, more research is required to address other issues in the automation process, like the delineation of flowlines, and the incorporation of estimation of volume to other important fields of study, like calculation of mass balance distribution in the Himalayas and the direct estimation of change in volume extent of glacial lakes based on change in areal extent.

Appendix A

Python script for the automated modeling of glacier volume based on laminar flow

The main Python script used for the development of an automated model for obtaining ice thickness distribution and glacier volume is given here. The script is compatible with all versions of Python and ArcGIS 10.x versions (10.1 and above). The code can be accessed at the following Github repository:

https://github.com/myxovirus/Automated-model-for-volume-estimation-of-glaciers-using-Laminar-Flow-Model-method

Key input parameters:

- Working directory
- Glacier boundary (from Rundolph Glacier Inventory)
- Surface velocity raster (from COSI-Corr software)
- Digital Elevation Model (DEM) raster (from ASTER DEM, SRTM)
- Contour shapefiles
- Flowline dataset (manually delineated)

Output parameters:

- Ice thickness distribution raster
- Total glacial volume

The Graphical User Interface (GUI) for the automated laminar flow model is now available to download at:

https://github.com/myxovirus/Automated-model-for-volume-estimation-of-glaciers-using-Laminar-Flow-Model-method

```
#Import modules
import arcinfo
import arcpy
import os, sys
import math
from arcpy import env
import arcpy.sa
from arcpy.sa import *

#Assign variable names to input parameters

##workspace = raw_input("Enter the path of your working directory: ") #folder
##flowlineDataset = raw_input("Enter the name of flowlines dataset: ")
#folder
##contourFile = raw_input("Enter the path of the contour shapefile: ")
#shapefile
##boundary = raw_input("Enter the path of glacier boundary polygon: ")
#shapefile
##velocityRaster = raw_input("Enter the path of velocity raster: ") #raster
##demRaster = raw_input("Enter the path of the DEM raster: ") #raster

#Example
workspace = "C:/Users/user/Desktop/PythonCode/test_2"
flowlineDataset = "flowline"
contourFile =
"C:/Users/user/Desktop/PythonCode/test_2/contour/rtopoly_g27.shp"
velocityRaster =
"C:/Users/user/Desktop/PythonCode/test_2/velocity_raster.tif"
boundary = "C:/Users/user/Desktop/PythonCode/test_2/boundary/glacier_27.shp"
demRaster = "C:/Users/user/Desktop/PythonCode/test_2/mosaic_utm_lp.tif"

#Set working environment
arcpy.env.workspace = workspace

#Make required folders in the current working environment

contourSplit = os.makedirs(workspace + "/" + "contour_split")
flowlineClip = os.makedirs(workspace + "/" + "flowline_clip")
velocityRasterClip = os.makedirs(workspace + "/" + "vel_ras_clip")
thicknessRasterClip = os.makedirs(workspace + "/" + "thickness_ras_clip")
mosaicRaster = os.makedirs(workspace + "/" + "mosaic_ras")
flowlineRaster = os.makedirs(workspace + "/" + "flowline_ras")
vectorFile = os.makedirs(workspace + "/" + "vector_file")
boundaryFile = os.makedirs(workspace + "/" + "boundary_file")
thicknessDis = os.makedirs(workspace + "/" + "thickness_dis")


#Add split field
outputField = arcpy.ValidateFieldName("Split_ID")
arcpy.AddField_management(contourFile, outputField, "TEXT")
arcpy.CalculateField_management(contourFile,       outputField,       "!FID!",
"PYTHON_9.3")


#Perform split analysis on input glacier contour file
```

```
arcpy.Split_analysis(in_features=contourFile,      split_features=contourFile,
split_field="Split_ID", out_workspace=workspace + "/" + "contour_split")


#Define input and clip feature classes
flowlineList = arcpy.ListFeatureClasses(feature_dataset = flowlineDataset)
#print "flowlinelist: " + flowlineList
contourSplitList       =       arcpy.ListFeatureClasses(feature_dataset       =
'contour_split')
#print "contourSplitList = " + contourSplitList


#Run a loop on each flowline
#Run a loop on each shapefile
#Create clip name for the indexed flowline and shapefile
#Create clip folder name for indexed flowline
#Clip analysis
#Note that required folder path needs to exist before running the code

for flowline in flowlineList:
    i = flowlineList.index(flowline)
    flowline = workspace + "/" + flowlineDataset + "/" + flowline
    outputClipFolder   =   workspace   +   "/flowline_clip"   +   "/flowline"   +
str(i).zfill(2)
    os.makedirs(workspace + "/flowline_clip" + "/flowline" + str(i).zfill(2))

    for contour in contourSplitList:
        j = contourSplitList.index(contour)
        contour = workspace + "/contour_split/" + contour
        outputClipName = "Clip" + str(j).zfill(3) + ".shp"

        arcpy.Clip_analysis(in_features = flowline, clip_features = contour,
out_feature_class = outputClipFolder+ "/" + outputClipName)

#Set working environment
arcpy.env.workspace = workspace + "/" + "flowline_clip"

#Define sub working spaces
clipFolderList = arcpy.ListWorkspaces()

#Define an empty matrix
matrix = []

for folder in clipFolderList:
    k = clipFolderList.index(folder)
    folder = os.path.normpath(folder)

    arcpy.env.workspace = folder
    clipList = arcpy.ListFeatureClasses()

    field = ['SHAPE@LENGTH']

    #Define constants
    iceDensity = 900
    scaleFactor  =  0.8  #ratio  between  the  driving  stress  and  basal  stress
along a glacier
    g = 9.8
```

```
    creepParameter = 3.24 * math.pow(10, -24)

    #Append matrix outside the nested loop
    #matrix.append([])
    list=[]
    for clip in clipList:
        result = arcpy.GetCount_management(clip)
        count = int(result.getOutput(0))

        if count != 0:
            with arcpy.da.SearchCursor(clip, field) as cursor:
                for row in cursor:
                    length = row[0]
                    slope = 100/length #for DEM elevation contours at 100 m
interval
                    a = math.atan(slope) #a is the slope angle
                    sina = math.sin(a)
                    constant = 1.5/(creepParameter * math.pow(scaleFactor, 3)
* math.pow((iceDensity*g*sina), 3))

        else:
            constant = 0

        list.append(constant)
                #matrix[k].append(constant)

    matrix.append(list)

print matrix

#Check out extension to retreive Spatial Analyst module
arcpy.CheckOutExtension('Spatial')

#Set working environment for analysis masks
arcpy.env.workspace = workspace

#Set scratch working space
env.scratchWorkspace = workspace

#Define velocity raster
velocityRaster = arcpy.Raster(velocityRaster)

#List masks: shapefile feature classes
contourSplitList = arcpy.ListFeatureClasses(feature_dataset =
"contour_split")

#Run a while loop over length of matrix
#Define folder name
#Make a subfolderfor every flowline

m = 0
while(m < len(matrix)):
    thicknessClipFolder = workspace + "/thickness_ras_clip/" + "flowline_" +
str(m).zfill(2)
    os.makedirs(thicknessClipFolder)
    m+=1
```

```
#Configure a loop for each mask in shapeFileList
#Define an environment mask
#Clip the raster with respect to the mask
#Save the clip file in output folder

for contour in contourSplitList:

        j = contourSplitList.index(contour)
        env.mask = workspace + "/contour_split/" + contour
        velocityClipName = "vel_clip_" + str(j).zfill(3) + ".tif"
        velocityClip = ApplyEnvironment(velocityRaster)
        velocityClip.save(workspace + "/vel_ras_clip/"+ velocityClipName)

        m=0
        while (m < len(matrix)):
            thicknessFolderName = workspace + "/thickness_ras_clip/" +
"flowline_" + str(m).zfill(2)
            thicknessClipName = "Clip" + str(j).zfill(3) + ".tif"
            thicknessClip = ((matrix[m][j]*velocityClip)/31536000)**0.25
            thicknessClip.save(thicknessFolderName + "/" + thicknessClipName)
            m+=1

#Check in extension
arcpy.CheckInExtension('Spatial')

#Check out extension
arcpy.CheckOutExtension('Spatial')

#Set working environment
arcpy.env.workspace = workspace + "/thickness_ras_clip"

#List working spaces inside the working environment
thicknessFolderList = arcpy.ListWorkspaces()


#Define velocity raster pixel type
pixelList1 = ["U1","U2","U4","U8","S8","U16","S16","U32","S32","F32","F64"]
pixelList2 =
["1_BIT","2_BIT","4_BIT","8_BIT_UNSIGNED","8_BIT_SIGNED","16_BIT_UNSIGNED","1
6_BIT_SIGNED","32_BIT_UNSIGNED","32_BIT_SIGNED","32_BIT_FLOAT","64_BIT"]


desc = arcpy.Describe(velocityRaster)
pixelType = desc.pixelType
index = pixelList1.index(pixelType)
pixelType = pixelList2[index]


#Configure a loop on every workspace or subfolder for each flowline
#Define the index of current subfolder
#Clean the path of the workspace with normpath
#Set the workspace as the working environment for ListRasters to function
#List thickness raster clips inside the subfolder
#Create a new subfolder in mosaic file for mosaic raster for working current
flowline
```

```
#Mosaic thickness raster clips to new raster
#Define current flowline shapefile as the environment mask
#Extract by mask the current flowline raster from the current mosaic raster
#Save the flowline raster in flowline raster folder


for folder in thicknessFolderList:
    i = thicknessFolderList.index(folder)
    folder = os.path.normpath(folder)
    arcpy.env.workspace = folder
    thicknessClipList = arcpy.ListRasters()
    mosaicFileName = "mosaic_" + str(i).zfill(2) + ".tif"
    mosaicFile = arcpy.MosaicToNewRaster_management(thicknessClipList, workspace + "/mosaic_ras", mosaicFileName, pixel_type = pixelType, number_of_bands = 1, mosaic_method = "MAXIMUM")
    arcpy.env.workspace = workspace
    env.scratchWorkspace = workspace
    flowlineList = arcpy.ListFeatureClasses(feature_dataset = flowlineDataset)
    env.mask = workspace + "/" + flowlineDataset + "/" + flowlineList[i]
    flowlineRaster = ApplyEnvironment(mosaicFile)
    flowlineRasterName = "flowline_ras_" + str(i).zfill(2) + ".tif"
    flowlineRaster.save(workspace + "/flowline_ras/" + flowlineRasterName)



#Check in extension
arcpy.CheckInExtension('Spatial')


#Set working environment
arcpy.env.workspace = workspace + "/flowline_ras"

#List every flowline raster
flowlineRasterList = arcpy.ListRasters()


#Configure a loop on every raster
#Name flowline vector
#Convert raster to point

for raster in flowlineRasterList:
    i = flowlineRasterList.index(raster)
    flowlineVectorName = "flowline_vec_" + str(i).zfill(2)
    arcpy.RasterToPoint_conversion(raster, workspace + "/vector_file/" + flowlineVectorName)


#Check out extension
arcpy.CheckOutExtension('Spatial')

#Set working environment
arcpy.env.workspace = workspace

#Convert polygon to line
glacierLine = arcpy.PolygonToLine_management(boundary, workspace + "/boundary_file/boundary_line.shp")
```

```
#Set working environment for analysis mask
env.scratchWorkspace = workspace

#Define analysis mask
env.mask = workspace + "/boundary_file/boundary_line.shp"

#Define input raster
inputRaster = demRaster

#Extract by mask glacier line raster from dem raster
tempRaster = ApplyEnvironment(demRaster)

#Assign 0 z-values to glacier line raster
boundaryLineRaster = tempRaster * 0

#Save glacier line raster
boundaryLineRaster.save(workspace + "/boundary_file/boundary_line_ras.tif")

#Raster to point conversion
arcpy.RasterToPoint_conversion(workspace                                    +
"/boundary_file/boundary_line_ras.tif",               workspace             +
"/vector_file/boundary_line_vec.shp")

#Check in extension
arcpy.CheckInExtension('Spatial')

#Check out extension
arcpy.CheckOutExtension('Spatial')

#Set working environment
env.workspace = workspace + "/vector_file"

#List input feature classes
vectorList = arcpy.ListFeatureClasses()


#Configure a loop on each feature class
#Create the search cursor as cursor and set field as grid code
#Configure a loop for each record or row in the table
#Delete the entire record with the conditional statement

for vector in vectorList:
    if vector != "boundary_line_vec.shp":
        with arcpy.da.UpdateCursor(vector, ["GRID_CODE"]) as cursor:
            for row in cursor:

                if row[0] == 1 or row[0] == 0:
                    cursor.deleteRow()



#Define an empty list for TopoPointElevation
#Configure a loop on each feature vector
#Use append tore each feature class and their respective fields in an array

inFeaturesFieldArray = []
```

```
for vector in vectorList:
    inFeaturesField = [vector, 'GRID_CODE']
    inFeaturesFieldArray.append(inFeaturesField)
    print inFeaturesFieldArray


#Store inPointElevations in the desired syntax
inPointElevations = TopoPointElevation(inFeaturesFieldArray)
inFeatures = ([inPointElevations])


#Check out ArcGIS Spatial Analyst extension license
arcpy.CheckOutExtension("Spatial")

#Topo to raster interpolation
OutTTR = TopoToRaster(inFeatures, cell_size = 30, minimum_z_value = 0)

#Save output Raster
OutTTR.save(workspace + "/thickness_dis/thickness_dis.tif")

#Check in extension
arcpy.CheckInExtension('Spatial')

#Check out extension
arcpy.CheckOutExtension('Spatial')

#Define environment mask
env.mask = boundary

#Define input raster
inputDistributionRaster          =          arcpy.Raster(workspace          +
"/thickness_dis/thickness_dis.tif")

#Apply environment mask to the input raster
finalRaster = ApplyEnvironment(inputDistributionRaster)

#Save final distribution raster
finalRaster.save(workspace + "/thickness_dis/final_thickness_dis.tif")

#Check in extension
arcpy.CheckInExtension('Spatial')
```

BIBLIOGRAPHY

- Bolch, T., Kulkarni, Kaab, A., Huggel, C., Paul, F., Cogley, G., Frey, H.,Fujita, K., Scheel, M.,Stoffel, M., Bajracharya, S., (2012). The State and Fate of HimalayanGlaciers. Science .Vol. 336 ,no. 6079, pp. 310-314.
- Huggel, C., Kulkarni, A.,(2002). Remote sensing based assessment of hazards from glacier lake outbursts: a case study in the Swiss Alps. Canadian Geotechnical Journal, 39(2): 316-330, 10.1139/t01-099.
- Banerjee, B., 2013. GLOF study using Remote Sensing and Ground Based Measurement Techniques, Indian Institute of Remote Sensing.
- Huggel, C.,Kääb,A., Haeberli,W., Teysseire,P.,Paul,F., 2002. "Remote sensing based assessment of hazards from glacier lake outbursts: a case study in the Swiss Alps." NRC Research Press. doi: 10.1139/T01-099.
- ICIMOD. 2010. Formation of Glacial Lakes in the Hindu Kush-Himalayas and GLOF Risk Assessment. International Centre for Integrated Mountain Development.
- ICIMOD. 2011. Glacial Lakes and Glacial Lake Outburst Floods in Nepal. International Centre for Integrated Mountain Development.
- Ukita, J., Narama, C.,Tadono, T., Yamanokuchi, T., Tomiyama, N., Kawamoto, S.,Nishimura, K. (August 2011). Glacial lake inventory of Bhutan using ALOS data: methods and preliminary results. Annals of Glaciology, Volume 52, Number 58, pp. 65-71(7).
- Dobhal, D.P.,Gupta,A.,Metha,M.,Khandelwal,D., 2013. "Kedarnath disaster: facts and plausible causes." Current Science no. 150. 51 Fujita, K.,Sakai,A., Takenaka,S., Nuimura,T.,2013. "Potential flood volume of Himalayan glacial lakes." Nat. Hazards Earth Syst. Sci. Discuss.
- ICIMOD. 2007. Impact of climate change on Himalayan Glaciers and Glacial Lakes: Case studies on GLOF and Associated Hazards in Nepal and Bhutan.
- Frey, H., 2011. Compilation and applications of glacier inventories using satellite data and digital terrain information. Geograph. Inst., Zürich.
- Hamilton, L.S., 2006. Protected areas in mountains. Pirineos 161, 151–158.
- Campbell, J.G., Pradesh, H., 2005. Inventory of glaciers, glacial lakes and the identification of potential glacial lake outburst floods (GLOFs) affected by global warming in the mountains of India, Pakistan and China/Tibet Autonomous Region. Int. Cent. Integr. Mt. Dev. Gp O Box 3226.
- Frey, H., 2011. Compilation and applications of glacier inventories using satellite data and digital terrain information. Geograph. Inst., Zürich.

- Govindha Raj, K. B., Remya, S. N., &Vinod Kumar, K. (2016).Inventory of Glacial Lakes and its Evolution in Uttarakhand Himalaya Using Time Series Satellite Data.Journal of Indian Society of Remote Sensing.pp-1-18
- Dobhal, D. P., Gergan, J. T., &Thayyen, R. J. (2004). Recession and morphogeometrical changes of Dokriani glacier (1962–1995) Garhwal Himalaya, India. Current Science, 86(5), 692–696.
- Richardson, S. D., & Reynolds, J. M. (2000). An overview of glacial hazards in the Himalayas. *Quaternary International*, *65*, 31-47.
- Gantayat, P., Kulkarni, A. V., & Srinivasan, J. (2014). Estimation of ice thickness using surface velocities and slope: case study at Gangotri Glacier, India. *Journal of Glaciology*, *60*(220), 277-282.
- Bhambri, R., & Bolch, T. (2009). Glacier mapping: a review with special reference to the Indian Himalayas. *Progress in Physical Geography*, *33*(5), 672-704.
- Yao,T.,Thompson, L., (July 2012). Third Pole Environment (TPE). Environmental Development, Volume 3,52-64. Gardelle, J., Arnaud.,Berthier, E., (January 2011). Contrasted evolution of glacial lakes along the Hindu Kush Himalaya mountain range between 1990 and 2009. Global and Planetary Change, 47–55.