ESTIMATION OF GLACIER STORED WATER IN BHAGA BASIN, HIMALAYAS

by

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(2015 - 20 - 025)

THESIS

Submitted in partial fulfilment of the requirements for the degree of

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DECLARATION

I, hereby declare that the thesis entitled **"ESTIMATION OF GLACIER STORED WATER IN BHAGA BASIN, HIMALAYAS"** is a bonafide record of research work done by me during the course of research and the thesis has not been previously formed the basis for the award to me of any degree, diploma, fellowship or other similar title, of any other University or Society.

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CHAPTER 1

INTRODUCTION

The frozen water part of the earth's climate system termed as the cryosphere, distributed over Earth in various forms such as seasonal snow, sea ice, ice sheet, glaciers, lake and river ice, permafrost, ice caps, ice shelves and ice crystals in the atmosphere (Vaughan *et al.,* 2013). One of the most critical form of the cryosphere is glaciers and glaciers cover about 10% of the land surface on Earth. They are functioning as the significant freshwater storehouse on Earth by holding a huge amount of water in it and nourishes the major river systems across the globe (Cuffey and Paterson, 2010). Glaciers are also playing a crucial role in regulating the Earth's climate system. They act as an important indicator of the changing climate. Hence, glaciers referred to as the 'natural thermometer' (Vaughan et al., 2013).

Various human activities such as the burning of fossil fuels, changing the land use patterns, deforestation, livestock production, unscientific agricultural activities, and industrial production leads to the increase in greenhouse gas concentration (especially CO_2 concentration) all over the world (Stern and Kaufmann, 2014). This is resulting in the accumulation of heat over Earth, called global warming (Trenberth, 2018). All these activities finally result in the changes in Earth's natural climate system (Last *et al.,* 1998). Mountain regions like Himalaya are observed as the most sensitive climate change hotspots (Kulkarni *et al.,* 2007). Recent studies are showing that the mountain regions are experiencing much higher warming than the global temperature rise (Negi *et al.,* 2016). This warming climate urges glacier retreating, snow and ice pack melting, floods, coastal erosion, and sea-level increase (Bajracharya *et al.,* 2007; Kaushik *et al.,* 2019).

The Himalayan-Karakoram region has the most massive glacier coverage outside the polar region, which is known as the third pole of the world. Himalayan glaciers are unique since they are located in high elevation zones in tropics. Most of the Himalayan glaciers are valley type and predominantly covered with debris. The Himalayan glaciers are the resources of freshwater to the mountain community especially during summer months, covering an area 40,755 sq.km. (Bolch *et al.,* 2012). Out of this, the Indian Himalayan glaciers covering an area of 23,314 sq.km (Kulkarni and Karyakarte, 2014). However, recent studies are reporting that the glaciers in Himalaya are retreating continuously due to rapid temperature rise (Tawde *et al.,* 2017; Kulkarni *et al.,* 2007) and glacier wastage in the future will continue even in the absence of global warming (Tawde *et al.,* 2016; Tawde *et al.,* 2017).

Snow and ice melt from Himalaya nourish the North Indian rivers and sustains the river flow throughout the year in Ganga, Brahmaputra, and Indus rivers (Kulkarni, 2014). It cannot be a permanent source of water because of the accelerated retreating behaviour glaciers. Glacier retreat also affects the water balance of the river basins (Kaser *et al.,* 2010). The warming trends of maximum, minimum and mean temperatures of the North-western Himalayan regions with a total increase of 0.9°C, 0.19°C and 0.65°C respectively strongly point towards the future risks (Negi *et al.,* 2016). The warming climate causes significant glacier mass loss which could lead to glacier retreat until a new equilibrium with the climate is attained. This will further disturb the glacier runoff by increasing the water flow during the starting periods of the warming climate and then decreasing near the end of the century (Huss *et al.,* 2008). Significant glacier area and mass loss followed by eventual disappearance of glacier ice are predicted in the Indian Himalayan region (Chaturvedi et al., 2014; Prasad *et al.,* 2019).

The health of the glaciers can be estimated by assessing various parameters such as glacier volume, mass balance and ice thickness. Sound knowledge of these parameters is required for several climatological as well as sea-level studies (Farinotti *et al.,* 2009). Glacier volume displaying an estimate of the amount of water stored by the glaciers (Huss *et al.,* 2008). Glacier ice thickness is required for the estimation of future glacier evolution, runoff projections, and sea-level increase (Frey *et al.,* 2014). Due to the rough Himalayan terrain and harsh climatic conditions, conventional methods cannot be carried out for the estimation of these parameters, which creates data gaps in the estimation. Remote sensing methods are used to overcome this limitation. The estimation of stored water will also help in the assessment of glacier melt runoff and water availability. A complete data set of the global glacier coverage became available after the release of the Randolph Glacier Inventory (RGI) in 2012, which can be used for the assessment of glacier volume (Frey *et al.,* 2014). The volume estimates vary to the glacier inventory used. Bolch et al., 2012 stated that the total volume of Himalayan glaciers is between 2300 and 6500 km^3, depending on the method of estimation. The superior quality of the glacier inventory assures a relatively more accurate estimation.

The commonly used methods to estimate glacier volure are Volume–area (V–A) relations (e.g., Chen and Ohmura, 1990; Bahr *et al.,* 1997), spatially distributed ice-thickness models (e.g., Farinotti *et al.,* 2009; Linsbauer *et al.,* 2012; Huss and Farinotti, 2012; Li *et al.,* 2012; Clarke *et al.,* 2013; McNabb *et al.,* 2012; van Pelt *et al.,* 2013) and slope-dependent ice thickness (Haeberli and Hoelzle, 1995). Volume-Area scaling method takes only one parameter, i.e., area of the glacier. Other components that affect the glacier volume, such as length of the glacier, ice thickness, slope of the terrain, etc. are not considered in this method (Frey *et al.,* 2014). Therefore, an alternative method using velocity, slope, and laminar flow equations is introduced to estimate glacier stored water (Manya *et al.,* 2016; Gantayat *et al.,* 2014).

The retreat of glaciers increases the concerns of society by creating new challenges. The disappearance of smaller glaciers in the lower altitude affects the runoff regime of rivers, which creates a dilemma in various hydroelectric projects settled downstream (Tawde *et al.,* 2017). Also, glacier shrinkage because of the warming in high mountain regions, causes the formation of glacier lakes (Kumar and Prabhu, 2012). Any changes in glacier volume will in turn, affect the area and volume of these lakes. This will trigger the occurrence of Glacial Lake Outburst Floods (GLOFs) (Maanya et al., 2016; Prasad *et al.,* 2019). An unexpected release of a considerable amount of water from these outbursts within a short time threatens the downstream community by harming their life, environment, and infrastructure (Remya *et al.,* 2019). Therefore, regular monitoring of glacier lakes is crucial. A proper understanding of glacier lakes is necessary for the preparation of mitigation activities for these hazards. It calls for the importance of the estimation of glacier stored water (Tawde *et al.,* 2017; Prasad *et al.,* 2019), understanding the probability of new lake formation and expansion of existing lake.

This study involves the estimation of total glacier stored water as well as predicting the potential glacier lakes in the Bhaga basin in the Western Himalaya using the laminar flow method. This method uses the relation between glacier surface velocity and ice thickness, two major parameters used to define the glacier dynamics. In the present study, the Himalayan Glacier Thickness Mapper (HIGTHIM) tool, based on Python 2.7, is used to estimate glacier depth and volume (Kulkarni *et al.,* 2019). The ArcPy module available from the ArcGIS 10.1 version is a multipurpose tool used for the estimation of glacier ice thickness. The required input parameters for the tool are modified glacier boundary, the spatial distribution of surface velocity, contour polygons, glacier flowlines, and Digital Elevation Models (DEM). It is possible to apply this tool for any glacier whose input data are available. This method can estimate the glacier ice thickness where mass-balance data are not available and help to assess the sustainability of Himalayan glaciers (Gantayat *et al.,* 2014; Remya *et al.,* 2019).

Bhaga basin is the sub-basin of the Chenab river basin located in the Lahaul-Spiti district of Himachal Pradesh, which lies on the Northern ridge of Western Himalaya. Highly snow-covered peaks encircle the glaciers in the Bhaga basin (Birajdar *et al.,* 2014). Because of the complex mountainous topography, few studies have done on the spatial and temporal characteristics of glaciers in this basin. Due to the complex topography and diverse land use, temperature and precipitation in the basin showing a high degree of spatial variability. Therefore, a sub-regional study of basins is needed. Recent studies suggest an increasing trend in annual mean temperature and a decreasing trend in precipitation, leads to the glacier shrinkage (Snehmani *et al.,* 2016). According to Kaushik *et al.,* 2019, the smaller glaciers in the Bhaga basin were retreating extremely fast in the lower altitudes. They predicted to lose large glacier areas that create new struggles to the freshwater availability. The downstream mountain community depends on the water from these glaciers for their livelihood. Therefore, it is necessary to have a proper estimate of the freshwater stored in glaciers. Proper awareness about the glacier stored water, and glacier ice thickness are also helpful to several other glaciological applications, mitigation activities, and socio-economic management practices (Farinotti *et al.,* 2009).

The present study focuses on the estimation of the spatial distribution of glacier ice thickness using the HIGTHIM tool with the following specific objective:

1. To estimate the glacier stored water in Bhaga Basin, Himalayas in India.

The essential steps used in the study are as follows:

1. Glacier boundaries obtained from Randolph Glacier Inventory (RGI-Version 6.0) which is an open-source, are manually modified using the latest Landsat images (Landsat 8) which are downloaded from USGS Earth Explorer, using Google Earth and ArcMap tools.

2. The modified boundaries are further used for estimation of the spatial distribution of surface velocity, calculated by sub-pixel correlation of Landsat images of consecutive years using the COSI-Corr tool.

3. Flowline is delineated along the contour polygon using ArcMap tools.

4. Run HIGTHIM tool using these input parameters for the estimation of the spatial distribution of glacier ice thickness.

5. Predicting the future potential lakes in the Bhaga basin.

CHAPTER 2

REVIEW OF LITERATURE

The Earth is a ‘Blue Planet’ since two-third of the earth’s surface covered by water (New, 2017). Water is a critical element of the earth’s system. All the living organisms on earth depend on water for their survival. Life on earth is not possible in the absence of water. The freshwater available on earth is only 3%, including the frozen water in glaciers, ice, and snow (Strahler and Strahler, 2013). The frozen water part of the earth's climate system is called the cryosphere, the most important freshwater reservoir (Vaughan, 2013).

Glaciers are known as the ‘River of Ice’. About 10% of the earth’s land surface covered with glaciers (Cuffey and Paterson, 2010). Glaciers are formed when the persistent body of dense ice continuously moves under its weight due to force of gravity. Glaciers can form in the regions, where winter snow accumulation exceeds summer ablation (Tielidze, 2017; Benn and Evans, 2010). Majority of glacier ice on earth are continental glaciers (ice sheets) discovered in the polar regions, and the rest are found on mountain ranges called alpine glaciers. Since variations in the climate system influence glaciers, they are considered as the most important and sensitive indicators of climate change (Dkhar and Tayal, 2013). Global sea level increase is closely associated with the state and stability of the cryosphere (Shum *et al.,* 2010).

2.1. CLIMATE & CLIMATE CHANGE

The long-term average of weather parameters conventionally taken over 30 years is termed as ‘climate’. It is an equilibrium between energy balance and global energy transports (Olbers.2012). ‘Climate’ can be expressed in many ways. A geologist sees climate as an external agent that forces many phenomena of interest. An agriculturist sees it as an influencing crop growth parameter, that shows a year to year variability. For a meteorologist, it is an average weather condition for a particular location over a period ranging from months to thousands or millions of years. In general, climate is the long term average of the weather parameters at a given region or area.

The long-term continous change (increase or decrease) to average weather conditions is simply reffered as climate change. United Nations Framework Convention on Climate Change (UNFCCC) defines climate change in Article 1, (1992) as ‘a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable periods.’

Climate change is occurring due to both natural and anthropogenic reasons. Modulations in the Milankovitch cycles, volcanic eruptions, ocean currents, solar variations, and some internal variabilities are the major natural causes of climate change. Various human activities are also changing the climate. Increase in the emission of CO_2 and other Greenhouse Gases, human-generated aerosols, land use pattern changes are some of the human inputs (Stern and Kaufmann, 2014) towards climate change. It has a widespread ill effect on the environment, socio-economic and related sectors by increasing the temperature, melting of snow and ice-covered regions, decreasing precipitation, increasing the frequency of flood, drought and heatwave incidents and decreasing cold waves (Narimisa *et al.,* 2018).

Global warming, the primary aspect of climate change is defined by Intergovernmental Panel on Climate Change (IPCC) as ‘the estimated increase in global mean surface temperature (GMT) averaged over 30 years, or the 30 years centred on a particular year or decade, expressed relative to pre-industrial levels unless otherwise specified’ (IPCC SR1.5, 2018). IPCC 5th assessment report (2014) states that most of the warming occurred on earth over the last 50 years is due to various human activities. Human activities are estimated to have caused approximately 1.0 ºC of global warming above pre-industrial levels (IPCC SR1.5, 2018). Since 1980, the successive three decades have been hotter than any other decade (IPCC, 2014).

Ruddiman (2005) observed that after the industrial revolution, our planet's surface temperature started to rise. The natural climatic state is altered because of human interventions. Changes in average atmospheric concentration leading to a remarkable transformation in the climate system. The concentration of greenhouse gases in the atmosphere increases rapidly and caused several changes in the Earth's natural environment. Greenhouse gases trapped more heat on Earth lead to global warming. Glacier ice is susceptible to varying temperatures. The warming scenario results in the melting of more glaciers and creates new environmental challenges to society (Kohler and Maselli, 2009).

2.2. IMPACTS OF CLIMATE CHANGE

Global climate change impacts are now visible on every corner of the world. Increased temperature, increased flood and drought events, shrinking glaciers, melting cryosphere, variations in the flowering season, mitigating animals, etc. are providing strong evidence. Climate extremes like heat waves, droughts, floods, forest fires, cyclones will intensify, and their vulnerability also increases in the future. Fluctuated ecosystems, increased risk to food security, decreased water availability, mortality, health-related problems, etc. are other dilemmas created by climate change (IPCC, 2014).

According to UNFCCC the "Adverse effects of climate change" means changes in the physical environment or biota resulting from climate change which has significant deleterious effects on the composition, resilience or productivity of natural and managed ecosystems or the operation of socio-economic systems or human health and welfare.

The rising temperature results in glacier retreat, melting of snow and ice packs, flooding in the downstream, coastal erosion, and finally sea level increase. Higher temperature causes greater than average summer melting of mountain glaciers. Diminishing snowfall along this leads to glacier shrinkage (Bajracharya *et al.,* 2007). Melting of massive ice sheets over Greenland and Arctic are also caused by global warming (Callaghan *et al.,* 2011).

India is also experiencing various impacts of climate change. Variations in Indian monsoon, glacier melt in Himalaya, eroding coastal region, increased incidence of natural disasters are a few of the climate change impacts in India (Balasubramanian and Birundha, 2012). The stability and reliability of North-Indian rivers will be threatened due to the warming climate. Increased glacier melt runoff over Indus and Ganga creates risks to the downstream community. Hydropower generation located downstream of the glacier-fed rivers in North India is also disturbed due to the changes in glacier melting (Tayal, 2019). Any changes in glacier volume will trigger the occurrence of glacier lake outburst floods, landslides, ice avalanches, etc. This again creates challenges to the mountain community (Tawde *et al.,* 2017; Prasad *et al.,* 2019).

2.3 HIMALAYAN GLACIERS

Mountains play an incredible role in regulating the circulation patterns and shaping the weather systems over a region (Beniston, 1997). About 27% of the Earth's land area is covered by mountains (Kapos *et al.*, 2000). Meybeck *et al.,* (2000) concluded that around 26% of the total world population is dependent on the mountain ecosystem.

In Sanskrit, the word 'Himalaya' means abode of snow. The Himalaya, the youngest and fragile mountain ranges across the globe, is known as the third pole of the Earth due to the largest deposition of snow and ice, after the Arctic and Antarctic. Because of the largest glacier extent, Himalaya acts as the critical source of water for major river systems in Asia, including Indus, Brahmaputra and Ganges, which nourish millions of people living in the adjoining regions. Himalayan glaciers are generally mountain/valley type glaciers. Himalaya consists of more than 15000 glaciers, covering an area of 40,755 sq.km on which the downstream community depends for their livelihood activities such as food production, electricity generation, irrigation, water supply, recreation and ecosystem functioning (Bolch *et al.,* 2012). Out of this area, 23,314 sq.km is spread in India (Kulkarni and Karyakarte, 2014). This mountain water tower also plays a very important role in regulating the Earth's climate system (Kulkarni, 2014).

The Hindu-Kush Himalayan region extends over 2500 km from west to east, across the Asian countries such as Afghanistan, Bangladesh, Bhutan, China. India, Nepal, Myanmar, and Pakistan (Le Forte, 1975). Northwestern Himalaya is mainly divided into three climatic zones as upper, middle, and lower Himalayan regions. The upper Himalayan region encompasses Karakoram range with extreme cold temperature and having large glacier mass. Dry snow precipitation with slight rainfall events in summer is the extensive climatic condition of this zone. The middle Himalayan region consists of Greater Himalaya, which holds numerous glaciers. Cold temperature with precipitation generally in the form of dry snow is the major climatic characteristic of this region. The lower Himalayan region is characterized by high precipitation and moderate temperature (Sharma and Ganju, 2000).

The major rivers in India such as Indus, Ganga, Brahmaputra, and their tributaries born from the Himalayan glaciers ensures the water security of North-Indian states. Majority of the North-Indian population trusted the meltwaters from these rivers. The Indus basin has the greatest runoff than the other two river basins (Immerzeel *et al.,* 2010). The significant runoff from the melting of snow and ice makes these North-Indian rivers perennial. Nonetheless, this is not a permanent source of water as the glacier extent decreases due to climate change (Tawde *et al.,* 2016; Tawde *et al.,* 2017). Since glaciers are highly sensitive to changing climatic conditions, they are considered as an important indicator of climate change. Cogley (2012) pointed out that the Himalayan water tower dries because of the greater summer ablation and lesser winter accumulation. The presence of black carbon also enhances the recession process by creating a warming atmosphere.

Various studies reveal that the Himalayan glaciers are retreating dangerously, except a few glaciers in the Karakoram region. The retreating rate varies with different regions. Around 4-30 % of the Himalayan glacier area has been reduced over the last 40 years. Current glacier stored water in Indian Himalaya is around 3651 Gt. The glacier mass is losing at a rate of 6.6 ± 1 Gt per annum (Kulkarni and Karyakarte, 2014; Kulkarni, 2014). An ‘eventual disappearance’ of the glacier is predicted in the Hindu-Kush Himalaya region. Due to the glacier retreating, a significant amount of stored water is missing from the Indian Himalayan glaciers (Tawde *et al.,* 2017; Kulkarni *et al.,* 2007).

Any changes in glacier volume increase the concerns about water security. Also, it creates new troubles in society by triggering the incidence of disasters like glacier lake outburst floods (GLOFs), landslides, and avalanches (Tawde *et al.,* 2017; Prasad *et al.,* 2019). Fujita and Nuimura (2011) calculated the Himalayan glaciers retreating rate based on some in situ measurements and concluded that glacier melting is more occurring in humid surroundings and less in arid conditions. Racoviteanu *et al.,* (2014) gave evidence that glacier area changes in dry regions of western Himalaya are seven times higher than the wetter eastern Himalaya, which are influenced by monsoons. For the glaciers whose accumulation is in higher altitudes than ELAs and situated in humid conditions showing a suppressed glacier wastage. The study shows that smaller glaciers located at small elevation regions with a simple geometry will vanish in the future.

Field expeditions are the traditional way of glaciological investigations. However, due to the harsh terrain of Himalaya, field-based estimations are very difficult to conduct (Kulkarni *et al.,* 2009). To overcome this limitation, the glacier inventory of Himalayan glaciers is prepared using several topographic maps and aerial photographs (Kulkarni, 2014). However, these methods also create lots of data gaps. The development of remote sensing techniques using advanced satellite sensors fixes most of the flaws in conventional methods. Many agencies have been formed for glacier inventory development such as World Glacier Monitoring Service, Global Land, and Ice Measurements from Space (GLIMS), GlobGlacier Project, Randolph Glacier Inventory, International Centre for Integrated Mountain Development (ICIMOD) (Bajracharya *et al.,* 2015). However, they are not a perfectly sound data source. Manual contributions are required for a more systematic glacier inventory. Landsat datasets are used widely for the analysis of glacier changes due to their higher spatial resolution, availability, and relatively good images. These remote sensing techniques provide only some baseline information about glaciers such as slope, elevation, aspect, glacier extension, and glacier type (Bajracharya *et at.,* 2015).

2.4. HIMALAYAN GLACIERS AND CLIMATE CHANGE

Himalayan region is considered as one of the most sensitive climate change hotspots in the world. Himalayan glaciers are already faced with the consequences of the changes in their environment (Kulkarni *et al.,* 2007; Tawde *et al.,* 2016).

Inter-governmental Panel on Climate Change (2007) stated that Earth's average surface temperature is supposed to increase 1.4 to 5.8 ℃ over the next century. Warming causes glacier retreat and the rate of retreat varies from glacier to glacier and region to region. Depending upon the climatological and geographic parameters the retreating rate of glaciers is estimated as 10 m to 61 m per year by using the scaling method (Kulkarni and Karyakarte, 2014). A rise in global mean temperature intensifies the glacier melting and leads to the formation of more potentially dangerous lakes, which creates catastrophic flood events to the mountain community. At least one Glacial Lake Outburst flood event between 3 to 10 years is recorded in the Himalayan region (Bajracharya et al., 2008). Another problem created by rapid melting is the greater river runoff during the initial phase of glacier retreat. But these initial increase in water supply will start to reduce after some period of time. This will shatter the water security. Change in the runoff pattern also affected the Himalayan ecosystem and the livelihood of people (Prasad *et al.,* 2019).

Global warming triggers the retreat of Himalayan glaciers. Recent studies showing that there is a negative mass balance trend is observed in Himalayan glaciers (Tawde *et al.,* 2017; Kulkarni *et al.,* 2007), except some in Karakoram ranges. A positive mass balance trend is recognized for a few glaciers in the Karakoram region. This reveals the advancing nature (a slight increase in glacier mass) of Karakoram glaciers (Gardelle *et al.,* 2012). Scherler *et al.*, (2011) explained that glacier retreating is influenced by topographical and climatic conditions. Glaciers that are showing stable or positive mass balance are occupying in westerly influenced regions. Glaciers located in North-East monsoon-influenced regions are unstable and retreating very fast. Increased glacier melt and results in sea-level rise. For most of the Himalayan glaciers, volume loss is more than expected due to incredible atmospheric warming.

Tawde *et al.,* (2017) estimated that total glacier volume loss in the Chandra basin can cause 0.18 mm of sea-level increase. An accelerated mass loss trend is observed in the basin. The investigation suggests that even in the absence of global warming, glacier retreat will continue in the future. Lee *et al.*, (2008) have explained how the normal environmental conditions over the Himalayan region are altered due to various human interferences. The presence of 'absorbing aerosols' and other anthropogenic activities accelerates climate change and causes severe damage to the Himalayan cryosphere (Kulkarni *et al.,* 2013).

Prasad *et al.,* (2019) estimated that 21 % of glacier volume reduced during 1984 - 2013 from the Satluj basin. The melting rate of glaciers increased after 1990. An increase in summer temperature and a decrease in winter snowfall is predicted for the Satluj basin, which warns that the Himalayas will witness a further glacier mass loss in the future. Smaller and Low - altitude glaciers are retreating very fast, and glacier loss will increase in the future warming decades. Around 95% of glaciers, in the basin stores less than 0.1 Gt of ice. Glacier melt runoff will initially increase and peaks by 2050, then will decrease. It will affect the contribution of melt runoff to the water reservoirs (Prasad et al., 2019). Sound knowledge of glacier stored water is very crucial for the development and implementation of climate change adaptation policies (Tawde *et al.,* 2017).

Snow and ice have positive albedo feedback, thus playing a crucial role in Earth's radiation budget. Any change in glacier area in turn influence sea level. Recent studies show that the Himalayan region is experiencing much higher warming than the global average temperature rise. Negi et al., (2016) highlighted that, as compared to the global mean temperature rise of 0.47 °C, the atmospheric temperature of Northwestern Himalaya increased by 0.65 °C from 1991 to 2015. Also concluding that, based on the variations in temperature and precipitation, glaciers are either growing or shrinking. There is an increasing trend in atmospheric temperature observed for the overall Himalayan region. Cooling over lower Himalaya is an exception. Nevertheless, the greater Himalaya region displayed a higher warming rate than the Karakoram Himalayan region. There is a decreased snowfall trend and an increased rainfall trend is observed over Northwestern Himalaya. But the total precipitation increased.

Usually, the ablation areas of glaciers are covered with debris. Thin debris cover over glaciers reduces the albedo of glacier ice. By this the melting rate of glaciers increases. Therefore, the estimation of the extent of glacier debris cover is important for runoff modeling studies. Banerjee and Shankar, (2013) evaluated the response of debris-covered glaciers with the warming climate. Several glaciers lose their volume and are currently shrinking. But they are not flowing and have a stable tongue. In the case of debris-free glaciers, the specific mass balance function decreases with altitude. For debris-covered glaciers, it is minimum in the ablation zone and then flattens or rises. Sherler *et al.,* (2011) summarizing that thick debris cover reduces the retreating rate of Himalayan glaciers. Hence debris-covered glaciers are not good indicators for recent climate change. But those glaciers with stagnant snout and negative mass balance trend speed up the formation of dangerous moraine-dammed lakes (Quincey *et al.,* 2009).

2.5. REMOTE SENSING AND GLACIER STUDIES

Remote sensing (RS) refers to obtaining information about objects or areas on the Earth’s surface without being in direct contact with the object or area. Remote sensing techniques use various wavelength regions of the electromagnetic spectrum (EMS) for taking images of the earth’s surface (Aggarwal, 2003).

The monitoring of glaciers in the Himalayan region by conventional methods is a challenging and laborious task due to the incredible mountain terrain and harsh climatic conditions. This calls for the need of remote sensing techniques in mapping and monitoring of glaciers. Satellite images can cover a large number of glaciers per image for long term period (eg; LANDSAT images) are available. Glacier features such as boundary, accumulation area, ablation area, Equilibrium Line Altitude (ELA), and moraine-dammed lakes can be precisely monitored using satellite images. Because of the significant difference between glacial and non-glacial features, mapping of glacier features are quite simple and easy. But for debris-covered glaciers, mapping of glacier snout is very difficult (Kulkarni *et al.,* 2009).

Using remote sensing techniques, glacier mass or volume and their changes with respect to climatic fluctuations can be monitored. Raup *et al.,* (2014) give a brief overview of how satellite images used to measure glacier parameters such as the location of glacier, glacier area, and length, glacier mass, and volume, velocity of glaciers, debris cover over glaciers, presence of lakes and ponds, etc. Proper assessment of these parameters helps to evaluate the relationship between climate change and glaciers. Different methods are used for the estimation of glacier volume. Scaling relation between glacier area and volume is used to estimate glacier stored water over large areas from satellite images (Bahr *et al.,* 1997). Since this method is not applicable for individual glaciers, advanced modeling techniques using the empirical relationship between glacier shear stress and topography have been introduced by Farinotti et al., (2009).

Climate change impacts on glaciers can be studied by analyzing equilibrium line altitude (ELA), a theoretical snowline at which accumulation is equal to ablation over a year. Pandey *et al.,* (2013) studied the relationship between climate change and ELA of glaciers in Northwestern Himalaya (Chandra- Bhaga basin) using remote sensing data and observed that ELA of glaciers is increasing due to rise in air temperature and decrease in winter snowfall. A higher snowline indicates the unhealthy condition of glaciers. Because it shows the negative mass balance trend.

Haq *et al.,* (2011) analyzed a set of multitemporal Landsat images to study the status of Gangotri glacier, one of the largest glaciers in Garhwal Himalaya. An overall reduction in glacier area with decreased accumulation area and increased ablation area is examined over Gangotri glaciers. The study concluded that remote sensing techniques and Geographic Information Systems (GIS) are very effective to monitor glaciers over large areas and glaciers that are hard to access.

Bajracharya *et al.,* (2014) describe the challenges in remote sensing technologies for the monitoring of glaciers. Boundary delineation through fully automatic techniques is a challenging process for debris-covered glaciers. For accurate delineation, digital elevation model (DEM) or topographic information are required. But, collecting cloud-free and snow-free images is very difficult. Ice thickness data generated by remote sensing showing high uncertainties. These uncertainties can be fixed by field validation. But the use of ground-penetrating radar (GPR) techniques in the Himalayan terrain is still very challenging.

2.6 GLACIER STORED WATER

Glacier volume is an important parameter, quantifies the amount of stored water. Studies on glacier ice volume and surface area are very essential to understand the relationship between glacier-climate interactions (Bahr *et al.,* 1997; Farinotti *et al.,* 2009). Awareness about total glacier volume and ice thickness distribution is also required in other fields of glaciology, like hydrology, modeling of regional climate, and glacier hazard assessments (Frey et al., 2014). There is an imbalance between the number of glaciers, area of glaciers and glacier volume. A large number of very small glaciers bearing a very small part of the total glacier volume. At the same time, a few large glaciers holding much of the total glacier stored water (Helfricht et al., 2019).

Huss et al., (2008) define the total glacier ice volume as the amount of water stored by glaciers in a given catchment, and the distribution of glacier ice thickness influences the hydrological characteristics of the basin. Glacier volume provides an estimate of the quantity of freshwater stored in the glacier reserves. Estimation of glacier ice thickness as well as helps to find out the glacier area loss and future changes in glacier geometry.

Spatial distribution of glacier ice thickness and volume can be estimated using different methods. Radio-echo sounding and borehole measurements are a few currently used field techniques to measure the thickness of glacier ice. But these methods are very expensive and laborious (Bahr *et al.,* 1997; Farinotti *et al.,* 2009). Utilization of these equipment over mountains like Himalaya is a tough task. Application of remote sensing techniques can overcome these difficulties of field estimation.

Ice volume is an important parameter required for the estimation of future glacier evolution, runoff projections, sea-level studies, and predicting impacts on the hydrological cycle (Frey *et al.,* 2013). Volume-Area relations (eg., Bahr *et al.,* 1997; Chen and Ohmura, 1990), slope-dependent ice thickness estimations (eg., Haeberli and Hoelzle, 1995) and ice thickness models (eg., Farinotti *et al.,* 2009; Huss and Farinotti, 2012; van Pelt *et al.,* 2013) are the commonly used methods to estimate glacier volume.

Bahr et al., (1997) proposed a method to connect unknown glacier ice volume and easily observable surface quantities. Glacier stored water over large areas can be calculated using the scaling relationship between ice volume and surface area. The volume-area power-law scaling method provides both practical and physically based methods to estimate the glacier volume. Apart from other volume-area scaling methods like Macheret and Zhuravlev, 1982; Chen and Ohmura, 1990, method developed by Bahr *et al.,* (1997) is more accurate. Scaling methods are extensively used because of their simplicity and easiness. Also due to the availability of measured and compiled data of glacier area (Frey *et al.,* 2014).

Bahr *et al.,* (2014) reviewed the general theory of scaling for glaciers. He discussed on the relationship between scaling techniques and other modeling methods, future development of scaling method, and advantages and limitations of the scaling method. The power-law scaling method is not suitable for individual glaciers or glacier branches or glacier complexes. This method does not consider other components affecting glacier volume such as length of the glacier, ice thickness, slope of the terrain, density, surface volume and shear stress, and it shows large variations from other volume estimation methods like perfect plasticity method and laminar flow method. If slope or elevation is relevant to apply, new scaling relationships should be prepared by extending the theory.

Farinotti et al., (2009) developed a method to estimate the distribution of ice thickness and total ice volume based on glacier mass turnover and principles of ice-flow mechanics (for Alpine glaciers) to overcome the disadvantages of scaling methods. It is very adaptable for individual glaciers in the small mountain ranges. This model is able to estimate the ice thickness from a given topography and suitable to estimate glacier bedrock topography where field measurements are difficult to conduct. But additional input data are required for different glaciers to adjust glacier mass turnover parameters. Although this modeling approach is accurate, still has large uncertainties. This cannot account for a specific glacier characteristic like glacier geometry or local climate and does not provide information on the spatial distribution of glacier ice thickness (Andreassen et al., 2015).

After the release of the Randolph Glacier Inventory (RGI) in 2012 (Pfeffer *et al.,* 2014) a complete data sets of global glacier coverage has become available, which can be used for the calculation of glacier stored water without relying on data extrapolation. Marzeion *et al.,* (2012) estimated the global glacier volume using the volume-area power-law scaling method based on the RGI. Huss and Farinotti, (2012) presented a method to estimate ice thickness distribution of all glaciers on the Earth based on RGI. Bolch et al., (2012) pointed out that, based on different volume estimation approaches used, the total ice volume in the Himalayan region varies between 2300 to 6500 km^3.

Frey et al., (2014) calculated the glacier volume in the Himalaya-Karakoram region ranges from 2955 to 4737 km^3 using scaling methods, slope dependent thickness estimation method, and two ice thickness distribution models (GlabTop2 and HF (Huss-Farinotti) model). This study revealed that the Karakoram region has greater ice thickness than the Himalayas. The eastern Himalayas contain the smallest ice volume. But western and central Himalayan regions showing similar volume estimates. Results from slope dependent thickness estimation method and ice thickness distribution models well agreed with local ice thickness estimates. But glacier volume calculated using the scaling approach showing large uncertainties.

Therefore, an alternative method using surface velocity, slope, and ice flow law called the 'laminar flow method' is introduced to estimate glacier stored water (Maanya *et al.,* 2016; Gantayat *et al.,* 2014). Different studies using the laminar flow method show the potential of this method to estimate the glacier ice thickness distribution, where mass balance data are not available (Gantayat *et al.,* 2014). Pradeep *et al.,* (2018) applied the laminar flow method to the glaciers in Sikkim Himalaya (55 glaciers) where velocity fields are satisfactory, and estimated the total glacier stored water in Sikkim Himalaya as 20 ± 3 Gt. Remya *et al.,* (2017) calculated the total glacier volume in the Parbati basin using scaling and laminar flow model. The total glacier volume in the Parbati basin (155 glaciers), covering an area of 377.16 km^2 is estimated as 21.07 km^3. Similarly, glacier stored ice in Spiti basin (for 114 glaciers) is estimated as 21.25 Gt (Pradeep *et al.,* 2017)

Glaciers in the Karakoram region are very unique. They are located in tropics, high altitude regions. Most of the glaciers in the Karakoram are valley type and most of them are covered with debris. Due to extreme weather and topographic conditions, remote sensing techniques are used for various assessments in the Karakoram region (Mathieu *et al.,* 2009). Singh *et al.,* (2019) attempted to estimate total glacier stored water in the Karakoram Himalaya using glacier ice thickness and areal extent, and the estimated values are validated using the GPR data. Ice thickness estimated using GPR is found close to satellite estimates. The estimated total ice volume in the Karakoram region is 1607 km^3 (equivalent to 1473 km^3 of water equivalent).

Proper estimations of volume changes is crucial because, it can trigger glacier hazards like glacier lake outburst floods (GLOFs) which harms the downstream people. (Prasad *et al.,* 2019).

2.7. LAMINAR FLOW METHOD

Glacier ice thickness is an important parameter required for the estimation of glacier stored water (Singh *et al.,* 2019). Several methods were used to the estimate of ice thickness of glaciers in past (Bahr *et al.,* 2014; Frey et al., 2014; Mcnabb *et al.,* 2012; Huss and Farinotti, 2012; Farinotti *et al.,* 2009). But these techniques having several uncertainties. Therefore, Gantayat *et al.,* (2014) developed a method (laminar flow method) to estimate the spatial distribution of glacier ice thickness using surface velocity, slope, and flow law of glacier ice. This ice thickness equation has been derived from the laminar flow equation of glacier ice and basal shear stress. Glacier surface velocity estimated using the remote sensing technique proposed by Leprince *et al.,* (2007).

The laminar flow method can be used to predict new glacier lake sites. Also, the enlargement of existing lakes. This method has the potential to provide important information for planning the mitigation strategies to reduce the impacts of Glacier Lake Outburst Floods (GLOFs) (Maanya *et al.,* 2016; Remya *et al.,* 2019).

The laminar flow method also has some limitations. This method is well suitable mostly for large glaciers in the Himalaya. Also has the ability to estimate ice thickness distribution where no mass balance data is available (Gantayat *et al.,* 2014). In the case of smaller glaciers, surface velocity cannot estimate because of the unseasonal snow, cloud, and debris cover (Prasad et al., 2019). Landsat images are not suitable for small glaciers due to their high spatial resolution. Therefore, surface velocity estimation for small glaciers is an unresolved task. Large efforts needed to collect cloud-free and snow-free Landsat images. Non-availability of convenient satellite images limits the surface velocity as well as thickness estimation for a few large glaciers also.

2.8. GLACIAL LAKE OUTBURST FLOOD (GLOF)

Glaciers all over the world are retreating due to global warming. In high mountainous regions glacier retreating leads to the formation of glacier lakes either behind the moraine or ice dams. Overdeepening of 'dams' results in the expansion of glacier lakes. Since these dams can breach out suddenly, it can cause a catastrophic flood in the downstream by releasing an enormous amount of water and debris. Such outbursts are called 'Glacial Lake Outburst Floods' (GLOFs). GLOF has the potential to discharge millions of cubic meters of water within a short time period. This challenges the mountain community by harming life, environment, and infrastructure (Kumar and Prabhu, 2012).

A lake outburst is triggered due to various reasons; sudden inputs of water into the lake by cloudbursts, ice or rock avalanches, earthquakes, landslides, the collapse of moraine dams due to the ice melting, dam overflow and self-destruction due to dam failure (Kulkarni *et al.,* 2018).

Bolch *et al.,* (2011) presented a comprehensive approach to identify potentially dangerous lakes (in the northern Tien Shan region) across a large area, using coupled remote sensing and geomorphometric analyses aided with Geographic Information System (GIS).

This study points out that glacier lakes are expanding due to the warming climate. Several lakes are identified as having the potential to create outburst floods. The number of potentially dangerous lakes are also increasing.

One of the earliest GLOF events reported in India was from Shyok glacier, Jammu and Kashmir, since 1835, mainly due to the sudden collapse of ice dams (Mason, 1929). Another flood event from an outburst of moraine-dammed lakes was reported at Shaune Garang glacier, Himachal Pradesh in 1981 and 1988 (Sangewar *et al.,* 1990). Recently in 2013, a flash flood event occurred in Kedarnath. It is because of the failure of the moraine dam of Chorabari lake, due to heavy rainfall (Dobhal *et al.,* 2013, Das *et al.,* 2015). A large number of glacier lakes are identified in the Himalayan region and some of these lakes are potentially dangerous (Remya *et al.,* 2019).

The sudden release of water from these outbursts changes the river discharges and these flood events sometimes last a few hours to several days. Hence continuous monitoring of glacier lakes and their expansion is very essential to mitigate possible glacier hazards. A method based on the surface velocity of glaciers, slope, and laminar flow equations are presented to identify and monitor glacier lakes by Maanya *et al.,* (2016) and Gantayat *et al.,* (2014). This method gives a more realistic approach to monitor the disastrous potential of glacier lakes.

Sharma *et al.,* (2018) proposed an empirical equation using the volume-area relationship to estimate the water storage capacity of moraine-dammed lakes in the Himalayan region. Substantial calving of glaciers due to varying climate is observed in the Himalayan region. This accelerates glacier retreat leads to the formation of new glacier lakes and the rapid expansion of present lakes. This study also presenting the importance of hydrodynamic modeling for flood simulation of potential glacier lakes.

Patel *et al.,* (2017) showed the substantial expansion of Samudra Tapu and Gepang Gath glaciers in Chandra basin, western Himalaya, during 1971-2014. The increase in area and volume of these glaciers are caused by the fast melting of the feeder glacier.

Yao *et al.,* (2012) analyzed the changes in moraine-dammed lakes in the North Himalaya, using the empirical equation of volume-area relationship. Analysis showing that the length and area of glacier lake (Longbasaba lake**)** increasing since the past three decades and the lake expanded drastically after 2000.

Maanya *et al.,* (2016) identified 12 sites for the potential lake formation in Drang Drung and Samudra Tapu glaciers in western Himalaya and also revealed the expanding nature of glacier lakes. This study is well demonstrating the advantages of remote sensing data like satellite images, DEM, and glacier boundaries, for the estimation of glacier ice thickness and glacier bed topography. Also, effectively predicts future lake formation, as well as the expansion of existing glacier lakes.

By adopting the same method, Remya *et al.,* (2019) attempted to estimate the volume of existing potential glacier lakes in Sikkim Himalaya (Tista river basin) and predicted the future expansion of these existing lakes. The study showing a large increase in glacier lake volume, with the potential to cause outburst floods in the mountain valleys. Future lake sites are also identified.

Proper knowledge about potential glacier lakes helps the policymakers and government agencies in the preparation of effective mitigation strategies, to improve the security measures and reduce the disaster risks for the mountain people.

CHAPTER 3

MATERIALS AND METHODS

3.1. STUDY AREA

The study area is the Bhaga basin, a sub-basin of the Chenab river basin situated in the Lahaul-Spiti district of Himachal Pradesh. The areal extent of Bhaga basin is lies between E76°56′16.253″ and E77°25′23.73″ longitude and N32°28′19.656″ to N33°0′9.887″ latitude and covering an area about 1644 km2 with an elevation range varies from 2901 m to 6410 m. Bhaga basin lies in the northern ridge of the Pir Panjal Range of the Western Himalaya (WH). According to the classification of WH by Sharma and Ganju (2000), Bhaga is in the middle Himalayan region. The basin is having around 319 glaciers occupying a glacierized area of approximately 320.23 km^2.

The study area is characterized by U shaped valleys, waterfalls, glaciers, and moraines. The basin is with very few vegetation and glaciers are spotted at the slopes. These glaciers nourishes the Bhaga river. The river discharge increases during the summer months, when the snow on glaciers at the higher elevation regions starts melting (Birajdar *et al.* 2014). Mulkila, Kelas Buk, Risang, Bugsubgang, Panchinala, Gangstan, and Patsio are the major glaciers in this basin. Also, the region has two major lakes, Suraj Tal and Patsio Lake (Birajdar *et al.* 2014; Snehmani et al., 2016).

Chandra (another sub-basin of Chenab basin) and Bhaga basins are located in similar climatic conditions. However, the glaciers in Bhaga are showing a higher retreating rate than Chandra basin (Pandey and Venkataraman 2013). The study area falls under the monsoon arid transition zone and marks the boundary of wet climate to its south and a dry climate to its north. Hence, the glaciers of this regions are considered as important indicators of northern monsoon intensity (Pandey *et al.,* 2013). The glaciers in the Bhaga basin influenced by the winds coming from South Asian monsoon in the summer and westerlies in the winters and making an ideal choice for studying the climatic response (Pandey and Venkataraman 2013). The location map of the study area is shown in Figure 1.

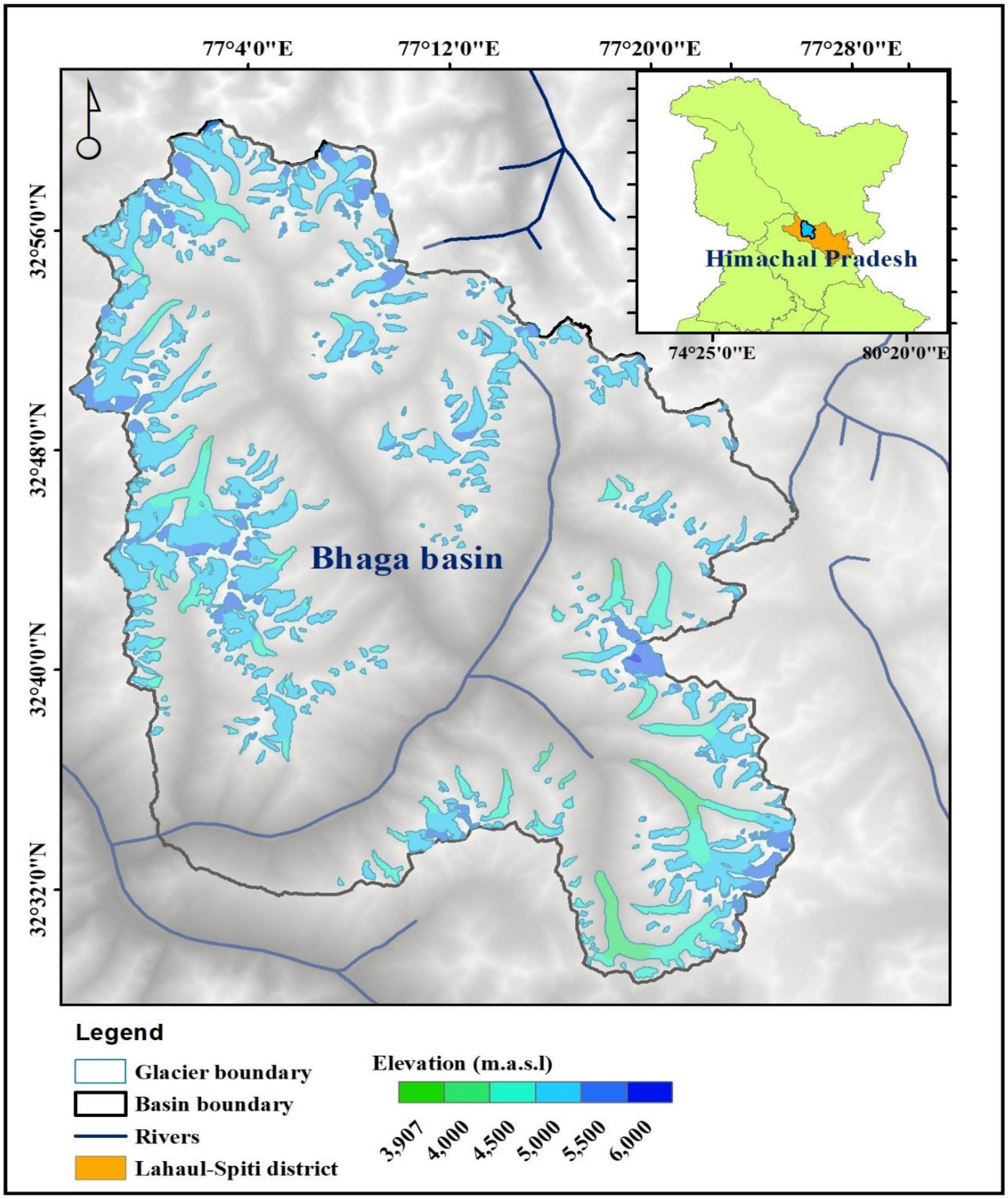


Figure 1. Geographical location of Bhaga basin, Lahaul-Spiti district, Himachal Pradesh. Glaciers in the basin are shown in blue borders. The basin consists of 319 glaciers covering an area of 320 sq. km. Colour scale indicates elevation range (m.a.s.l).

3.2. METHODOLOGY

The study involves the estimation of total glacier stored water in the Bhaga basin using the laminar flow method. This method uses the relation between glacier surface velocity and ice thickness. Ice thickness distribution was estimated using a semi-automated tool called Himalayan Glacier Thickness Mapper (HIGTHIM). Glacier boundary, surface velocity, contour polygons, glacier flowlines, glacier moraine, and digital elevation model (DEM) are the preliminary inputs of this tool. The data sets and software used in this study are given in Table 1 and Table 2. A complete methodology is shown in Figure 2.

DATASETS
Landsat 8 (OLI/TIRS) imagery (2013 – 2019)
ASTER DEM
RGI 6.0

Table 1. Required data sets

SOFTWARE
HIGTHIM tool (Python 2.7 based)
ArcGIS 10.1
ENVI (integrated with COSI-Corr tool) 4.5
Google Earth Pro

Table 2. Required software

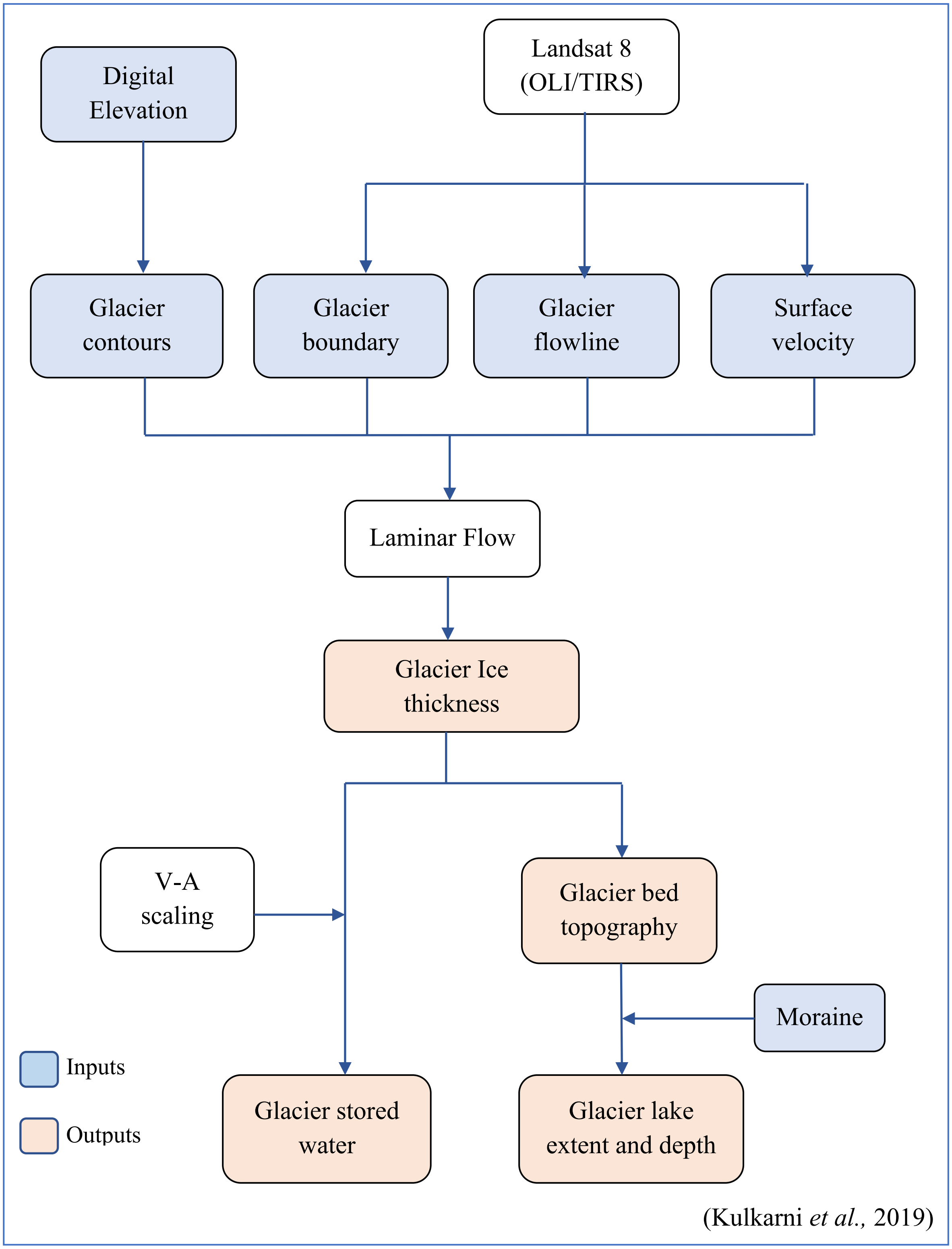
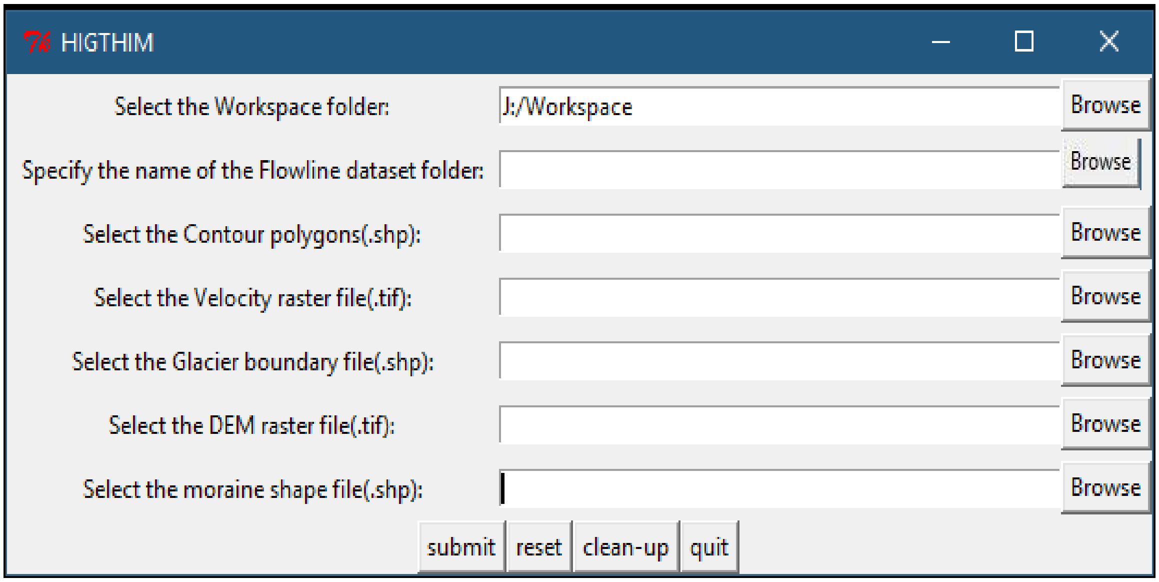


Figure 2. Flowchart showing methodology for the estimation of glacier stored water and identification of potential glacier lakes.

3.2.1 HIGTHIM TOOL

Spatial distribution of glacier ice thickness and potential sites for glacier lake formation were identified using a semi-automated tool called Himalayan Glacier Thickness Mapper (HIGTHIM) tool (Figure 3.). This tool is written in python language utilizing the Arcpy module from ArcGIS 10.1 software. Glacier boundary, flowlines, moraines, velocity, DEM, and contour polygon are the input parameters required for this tool. All inputs should be in the same projected coordinate system, and there should be no empty files (Kulkarni et al., 2019).



Select the Workspace folder: J:/Workspace
Specify the name of the Flowline dataset folder:
Select the Contour polygons(.shp):
Select the Velocity raster file(.tif):
Select the Glacier boundary file(.shp):
Select the DEM raster file(.tif):
Select the moraine shape file(.shp):

Figure 3. HIGTHIM tool GUI (Graphical User Interface). Glacier flowlines, contour polygons, velocity raster, glacier boundary, DEM and moraines are the inputs given to

3.2.1.1. GLACIER BOUNDARY MODIFICATION

Glacier boundaries were assessed from the Randolph Glacier Inventory (version 6), a publically available data source *(https://www.glims.org/RGI/)*. These downloaded RGI boundaries were then modified manually using Google Earth and ArcMap tools with the help of the latest satellite images. RGI boundaries are having some uncertainties like the misinterpretation of seasonal snow cover and debris cover. Regional glacier shrinkage information excluded in RGI. The use of satellite images for different periods also causes uncertainties in the glacier inventory. Thus, appropriate revision of RGI boundaries was needed in the present glacier studies for better results (Pfeffer *et al.,* 2014).

The glaciers were manually delineated on satellite imageries using the criteria explained by Nuimura *et al.,* (2015). During the boundary modification, the glacier mass only below the bergschrund (bergschrund is a term used in glaciology for the highest nearly stationary crevasse developed at the glacier heads (Mair, R. and Kuhn, M. 1994)) was considered as the glacier part. Steep headwalls were also eliminated (Nuimura et al., 2015). Significant differences in the spectral reflectance between glaciated and non-glaciated areas on false-colour-composite imageries simplify the mapping procedure of debris and snow-free glaciers (Kulkarni et al., 2009). Debris-covered glaciers should delineate very carefully. Identification of exposed ice cliffs over debris-covered glaciers is useful for the digitization of debris-covered glaciers. This was effectively carried out using high-resolution Google Earth images (Nuimura *et al.,* 2015).

Landsat 8 (OLI/TIRS) imagery during September and October months were downloaded from the United States Geological Survey (USGS) website (*https://earthexplorer.usgs.gov/*) for the modification of RGI boundaries. Images during the post-monsoon months had minimum snow and cloud cover. These modified glacier boundaries were used in the HIGTHIM tool to estimate the spatial distribution of ice thickness. Precise glacier boundaries are essential for the delineation of glacier flowlines and moraines, also in calculating the area of glaciers.

3.2.1.2. SURFACE VELOCITY ESTIMATION

Surface velocity was estimated using the sub-pixel correlation of Landsat images using COSI-Corr (Co-registration of Optically Sensed Images and Correlation) option in a freely available software module integrated with ENVI (Environment for Visualizing Images) (*http://www.tectonics.caltech.edu/*). In this algorithm, two satellite images of consecutive years were cross-correlated in the phase plane on sliding windows to get the best correlation. This algorithm is explained in detail by Leprince et al. (2007). The correlation was carried out in a 32×32 pixel sliding window with a step size of two pixels. The output file had three images: north/south displacement image, east/west displacement image, and signal to noise ratio (SNR) images. SNR images express the quality and accuracy of the correlation. All the pixels with SNR < 0.9 were discarded because SNR value < 0.9 were considered as erroneous. From the two displacement images, a vector field was generated, representing the direction of the glacier flow. Proper alignment of displacement vectors along the length of the glacier was then verified. A Euclidean expression was applied when the vector field is verified to be satisfactory, to find out the magnitude of resultant displacement. The annual surface velocity was estimated using the acquisition time of the two satellite images. Since the satellite images were of two consecutive years, the estimated displacement corresponds to the annual glacier velocity. All the pixels were having velocity < 85 m yr^{-1} also discarded. This sub-pixel correlation was applied to 64 glaciers (an area greater than one sq. km) in the study area. For the remaining 255 glaciers, surface velocity could not be estimated by this method due to the smaller size of glaciers and less availability of adequate satellite images.

3.2.1.3. DIGITAL ELEVATION MODEL (DEM)

ASTER DEM (Advanced Spaceborne Thermal Emission and Reflection Radiometer Digital Elevation Model) was used in this study, which was downloaded from the USGS Earth Explorer website for the Bhaga basin. This must ensure that the DEM should cover all the glaciers in the study area. The coordinate system of DEM is changed to WGS 1984, UTM zone 43N in ArcMap.

3.2.1.4. CONTOUR POLYGON CREATION

Contour lines are imaginary lines that connect the same elevation points. Contour polygons in this investigation were used to find out the values of elevation areas between two contour elevations. Contour polygons represent in maps as colour-coded polygons which makes visualization and analysis easier.

Contour polygons not only used as an input for the estimation of the spatial distribution of glacier ice thickness but also, help in the delineation of the glacier flowlines. Contour polygons are created using the Digital Elevation Model (DEM) with the help of ArcMap tools. Using **extract by mask** function, glacier boundaries are extracted from DEM. Then using reclassify function masked DEM for the glacier boundary is reclassified to 100m elevation bands. This reclassified DEM is then converted into contour polygons. The output file should be saved as shapefile (.shp).

3.2.1.5. FLOWLINE DELINEATION

Glacier flowline is a line that represents a spatial pattern of the glacier flows from the top of the glacier to its snout region. Glaciers are having a major central flowline and tributary flowlines. The number of tributary branches varies as per the branches (tributaries) and size of the glaciers. The smallest glacier mainly has the centerline.

In this study, the flowlines were delineated manually using Landsat 8 (OLI/TIRS) imagery with the help of ArcMap tools. Satellite images for September and October used to avoid cloud and snow cover. Flowlines were digitized manually by drawing polyline perpendicular to the contour polygons by considering the medial moraine on the glacier. The centerline delineated by connecting the highest and lowest points of the glacier viz, from the top to terminus. The tributary lines were digitized from bottom to top perpendicular to the contour lines. Flowlines should delineate at 150m distance from the glacier boundary. Also, each flow line should be separated from 300-400m. If the glacier trunk is wide enough to accommodate more than two flowlines, multiple flowlines can be drawn by keeping the distance criteria for flowlines. Each flowline should be created as an individual shapefile to avoid the model error. The ice thickness for the glacier was estimated from surface velocity, along the flowlines.

3.2.1.6. MORAINE DELINEATION

Glacier moraines are an area of debris accumulation (dirt, rocks, etc.) over the glacier surface that is either fallen over the surface or sedimented along with the movement of the glacier. Medial moraine, lateral moraine, and end moraines are common glacier moraines. A retreating glacier leaves moraine behind it and is visible long after deglaciation. Glacier receding causes the formation of moraine-dammed lakes, which can create a catastrophic flood in the mountain valleys (Maanya *et al.,* 2016).

In the present study, glacier moraines were digitized manually using Landsat 8 (OLI/TIRS) imagery in Google Earth Pro as well as ArcMap. Moraine delineation should start from the terminus till the mid-ablation region of the glacier. Moraines were identified by changes in the spectral reflectance between glacier and moraine using False Colour Composite (FCC) images. Digitized moraine should be saved as a shapefile.

3.2.2. ICE THICKNESS ESTIMATION

Glacier ice thickness along the flowline was estimated using the laminar flow equation;

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

where $\boldsymbol{H}$ is ice thickness (m), Us surface velocity. (Swaroop *et al.,* 2003). $\boldsymbol{\rho}$ the ice density which is assigned a constant value of 900 kg m^{-3}, $\boldsymbol{g}$ is the acceleration due to gravity which is 9.8 m s^{-2}, $\boldsymbol{A}$ is a creep parameter (which depends on temperature, fabric, grain size, and impurity content), assigned a value of 3.24×10^{-24} Pa^{-3} s^{-1} (Cuffey and Paterson, 2010), $\boldsymbol{f}$ is the shape factor (ratio between the driving stress and basal stress along a glacier) with a constant value of 0.8 (Haeberli and Hoelzle, 1995), and $\boldsymbol{\alpha}$ is the slope angle. Slope ($\boldsymbol{\alpha}$) is estimated from ASTER DEM at 100m elevation contours intervals, from which depth is calculated for an area between successive 100m contours (Gantayat *et al.,* 2014).

The above ice thickness equation is developed by Gantayat *et al.,* (2014) from the equation of laminar flow of glacier ice and basal shear stress.

Equation of laminar flow:

$$\boldsymbol{U_s} = \boldsymbol{U_b} + \frac{\mathbf{2A}}{\boldsymbol{n}+\mathbf{1}}\,\boldsymbol{\tau_b^n H}$$

(Cuffey and Paterson, 2010)

where U_s and U_b are surface and basal velocities, respectively. H is the ice thickness (m), A is the creep parameter (3.24x10-24 $Pa^{-3}s^{-1}$ for temperate glaciers), **n**, Glen's flow law exponent and is assumed to be 3.

Basal stress:

$$\tau_b = f\rho g H \ \sin\alpha$$

where ρ is the ice density (900 kg m^{-3}), g is the acceleration due to gravity (9.8ms^{-2}) and f is a scale factor with a constant value of 0.8.

The thickness along the flowlines for each sectional area between successive 100 m contours was interpolated over the entire glacier using thin-plate spline interpolation, where depth at the boundary was considered as zero. Abrupt changes in spatial ice thickness were removed after smoothening using a 3×3 kernel in ArcGIS.

3.2.3. V-A SCALING AND GLACIER STORED WATER ESTIMATION

The volume of the glacier was computed by multiplying the area of the glacier with the summation of ice thickness at all the pixels of the glacier. For 64 glaciers, the glacier volume was estimated using this velocity-slope method. Volume-Area power-law scaling method was applied to estimate the glacier stored water for those glaciers, the velocity-slope method could not be applied. For 255 glaciers *V-A* scaling method was used to estimate glacier volume, based on which the volume estimate developed using the velocity-slope method.

According to power law, the glacier volume (V) is related to the glacier area (A) and can be expressed as:

$$V = C_A \times A^{\gamma}$$

where γ is the scaling exponent and C_A is the constant of proportionality ($km^{3-2\gamma}$).

As mentioned earlier, velocity-slope method was applied for 64 glaciers. Out of these, 59 glaciers had an aerial extent below 10 sq. km. Outputs from these 59 glaciers along with 298 glaciers from Beas and Satluj basins (Prasad *et al.,* 2019) were used to derive the power-law constants for the Bhaga basin glaciers. This new *V-A* power-law scaling equation was then applied to the remaining 255 glaciers to estimate their volume. The estimated glacier volume was then converted into glacier stored water by multiplying it with the density of water.

3.2.4. PREDICTING THE POTENTIAL LAKES

Glacier recession leads to the formation of glacier lakes at glacier bed over deepening sites. These lakes can trigger GLOF events. Therefore, it is imperative to identify potential glacier lake sites (Gantayat *et al.,* 2014).

Depending upon the surrounding topography of the glaciers, lakes can form. Hence the area up to lateral moraines is considered for the identification of potential lake sites. These moraines were manually digitized by visual interpretation, as mentioned earlier. In the case of existing lakes, the depth of the lake was estimated using the shape and maximum depth, by assuming that depth decreases up to the lakeshore (Hollister and Milstead, 2010; Remya et al., 2019).

Glacier bedrock topography was obtained from the difference between the distribution of ice thickness and surface topography. Subsequently, the glacier over-deepening pointed out by filling the sinks in the glacier bed using the hydrology tool 'fill' in ArcGIS. This process smoothens depressions. The area and volume of the over-deepening were quantified by subtracting the filled bed from the original bed topography. Future lake formation was identified from the topography up to the moraines (Maanya *et al.,* 2016).

CHAPTER 4

RESULTS

4.1. GLACIER INVENTORY IN THE BHAGA BASIN

Glacier boundaries were acquired from the open-source Randolph Glacier Inventory version 6 (RGI). As per the downloaded RGI boundary data, the Bhaga basin was having 306 glaciers with a glaciated area of 368 km^2. Following RGI, the percentage of the glaciated area of the Bhaga basin was 22%. Pfeffer *et al.*, 2014 pointing out that the RGI boundaries should be modified regionally to get more accurate glacier outlines. The downloaded RGI boundaries were manually modified using good quality satellite images. Debris free glaciers were mapped by observing the spectral reflectance of glaciated and non-glaciated fields on Landsat imagery. Delineation of debris-covered glaciers is a challenging task. High-resolution Google Earth images were utilized for this purpose. Snow free and cloud-free images were picked to mark the glacier outlines faultlessly. We have identified 319 glaciers after the boundary modification. These glaciers are covering an area of ~320 km^2 and it is around 20% of the basin area. Here, we had considered all perennial snow masses as glaciers (Nuimura *et al.,* 2015; Racoviteanu *et al.,* 2009). Therefore, the number of glaciers has increased than RGI boundary. After the boundary modification, a 2% reduction in glacier area was observed. It is because of the uncertainties in RGI glacier boundaries (Pfeffer *et al.,* 2014). Systematic glacier boundaries are mandatory for the stored water estimation as well. Glacier boundary before and after the modification for the glacier no. 112 is shown in Figure 4 as an example.

The glacier boundaries modified from RGI boundaries for individual glaciers are displayed in Figure 5. The modification results showing that majority of the glaciers in the study area having an area less than 0.1 km^2. Only 25 glaciers possess a glaciated area greater than 3 km^2. More than 250 glaciers fall below the 1 km^2 glacier area. 92 smaller glaciers (including perennial snow cover) identified in the basin, which is also included in stored water estimation. Glaciers above 1 km^2 were considered for the estimation of glacier ice thickness. The number of glaciers belongs to the different glacier area classes are given in Figure 6. The area for individual glaciers is also specified in appendix I.

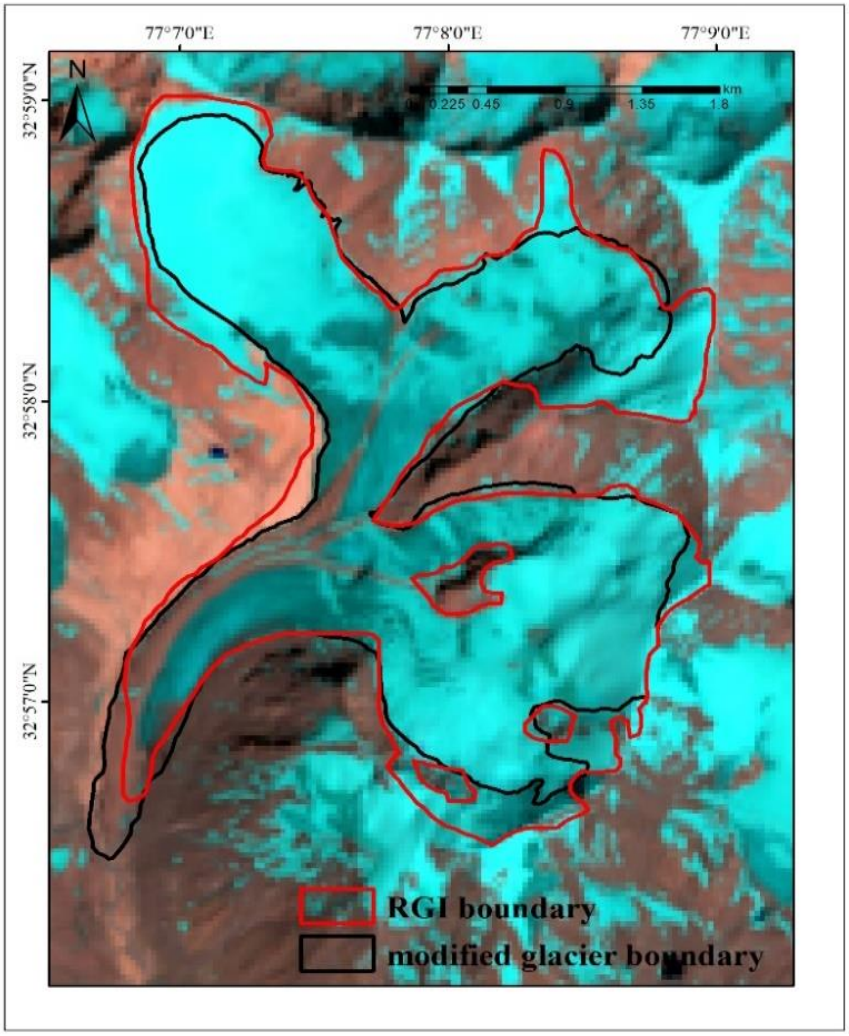


Figure 4. Glacier boundaries of the glacier no. 112. Downloaded RGI boundary is displayed in red borders. Modified boundary is shown in black borders. The glacier terminus was identified using Google Earth imagery, by monitoring the ice cliffs. Upper accumulation area mapped by considering the bergschrund line (Nuimura et al., 2015)

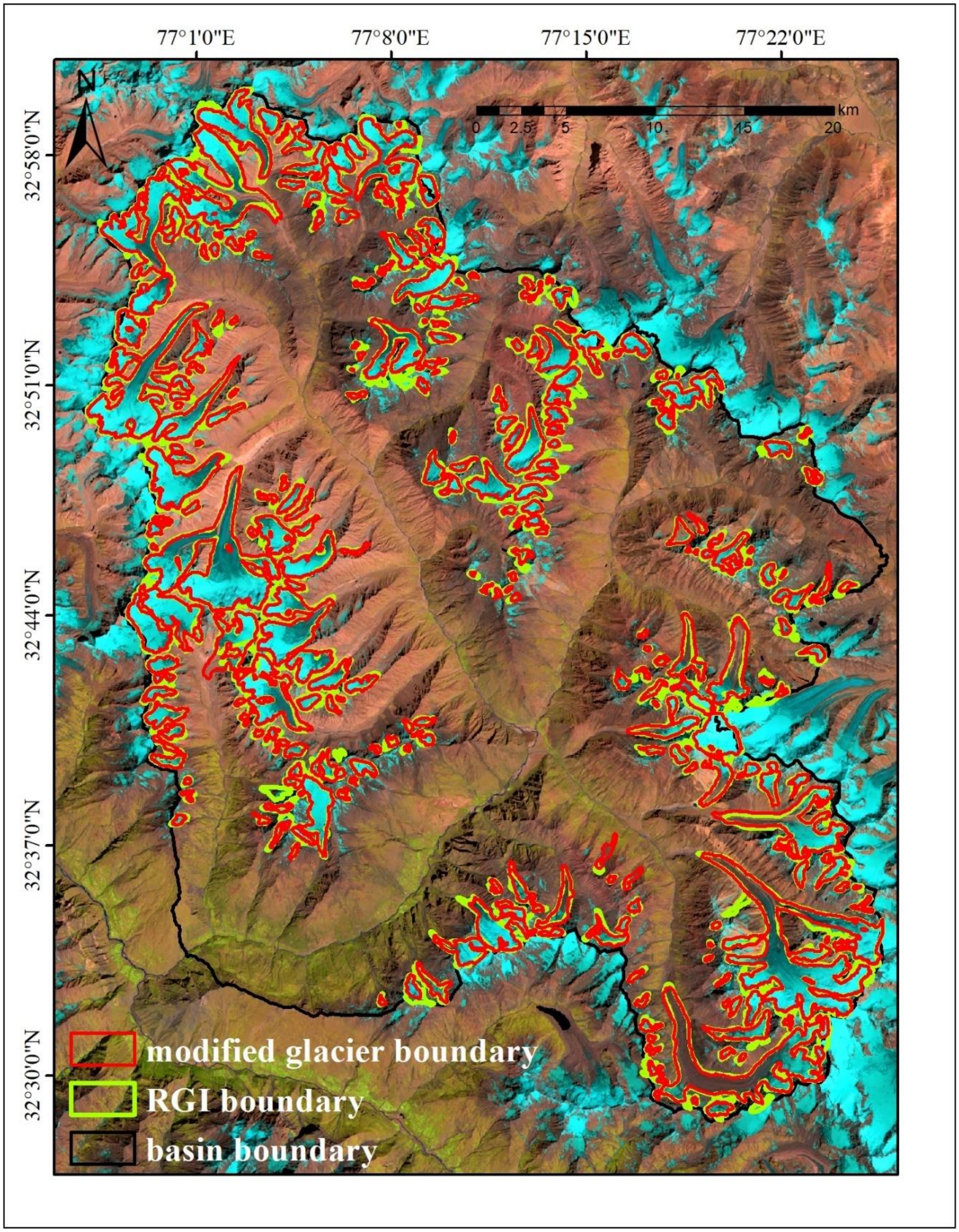


Figure 5. Downloaded RGI boundaries and modified glacier boundaries for individual glaciers in the Bhaga basin are shown with green and red borders respectively.

4.2. SPATIAL DISTRIBUTION OF SURFACE VELOCITY

The surface velocity of 64 glaciers was estimated using the COSI-Corr tool and Landsat images. Our estimate of the mean velocity in the Bhaga basin was ~8.1 myr^{-1}. The spatial distribution of the surface velocity of individual glaciers in the Bhaga basin is shown in Figure 9. Velocity is higher in the upper trunk region of the glaciers and gradually decreases to the lower reaches. The velocity estimates showing that the highest mean surface velocity is observed for the glacier no. 203 and its mean velocity is ~19.5 myr^{-1}. The lowest mean velocity was estimated for the glacier no. 9, having mean surface velocity as ~3.5 myr^{-1}. Highest surface velocity was observed for the largest glaciers in the basin (in most of the cases). The relationship between surface velocity and area of glaciers is shown in Figure 7. The mean glacier velocity was ranging from 5 to 10 myr^{-1} (44 glaciers). The number of glaciers in different velocity ranges is given in Figure 8. Mean surface velocities of individual glaciers are tabulated in table 3.

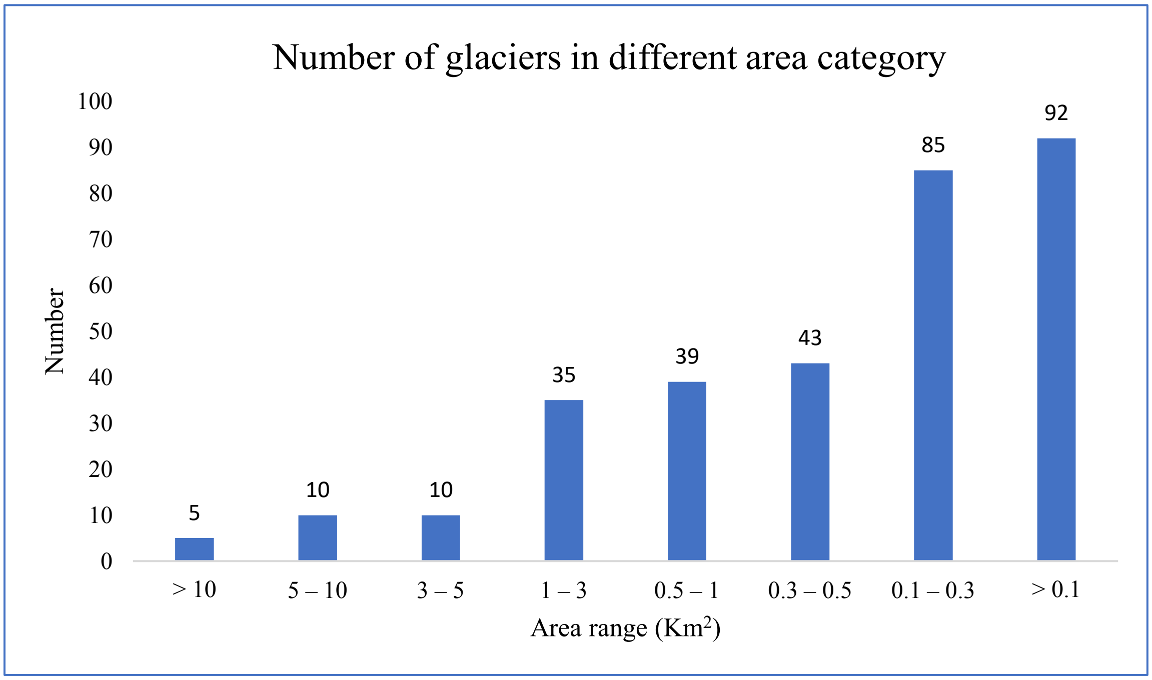


Figure 6. Histogram showing the number of glaciers in different area categories. Most of the glaciers in the basin having area less than 0.1 km^2. Glaciers above 1 km^2 area are considered for laminar flow method.

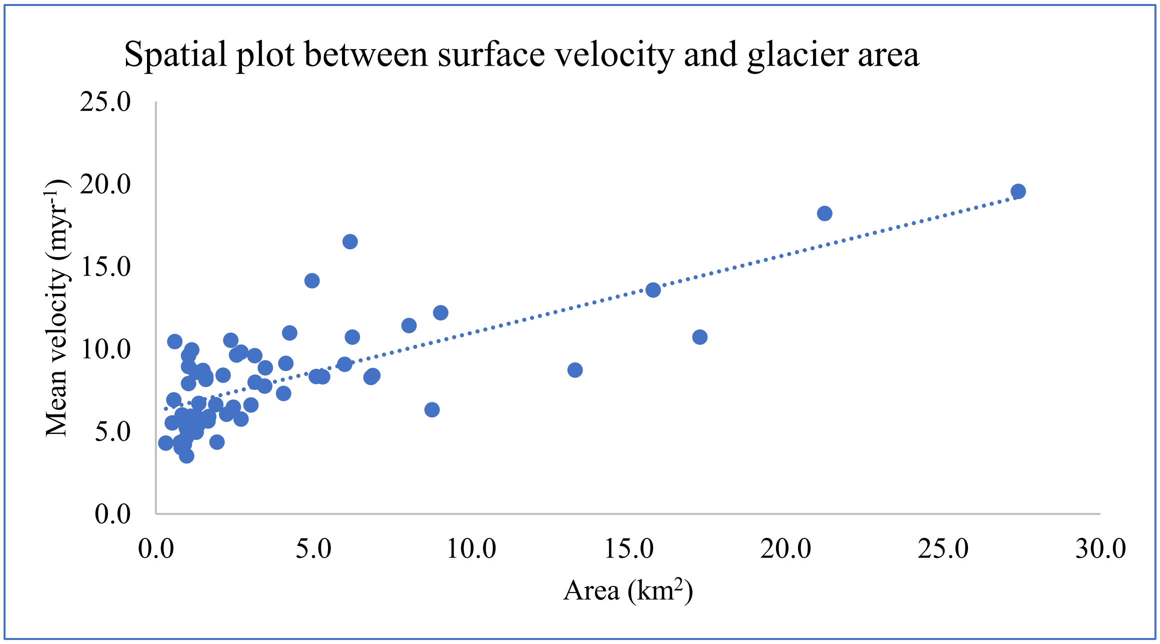


Figure 7. The relationship between glacier surface velocity and area is shown in the scatter plot. Glacier area and surface velocities are directly related (major trend).

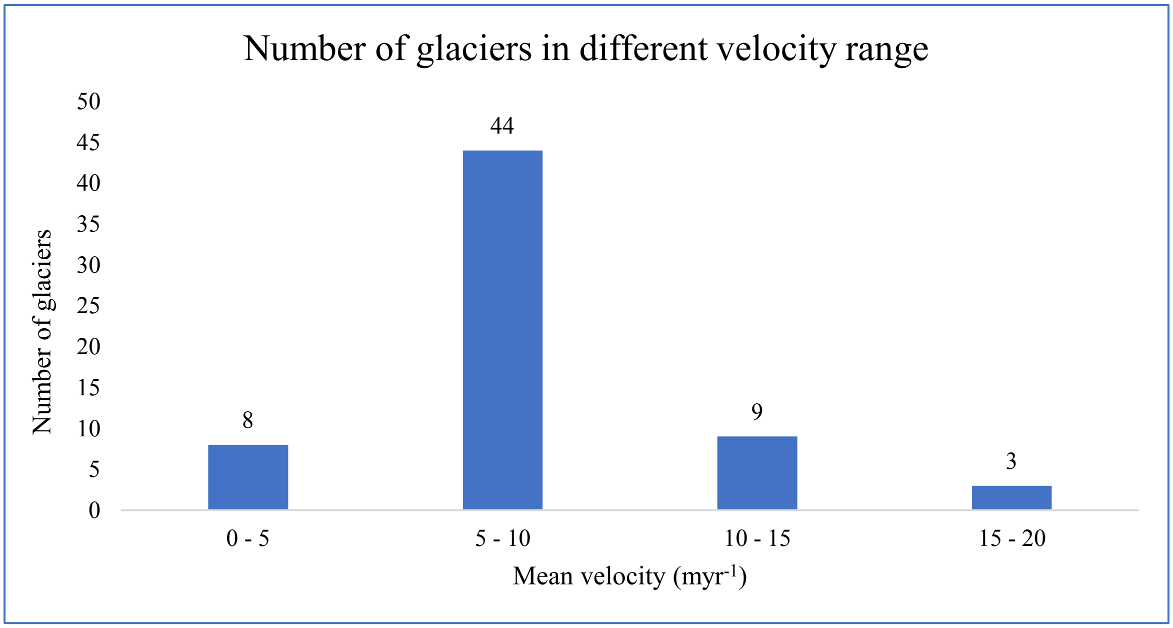


Figure 8. The number of glaciers in different velocity (mean velocity) categories is shown as histograms. The mean velocity of glaciers ranges between 3.5 to 19.5 myr^{-1}. Most of the glaciers in the basin possess 5-10 myr^{-1} average surface velocity.

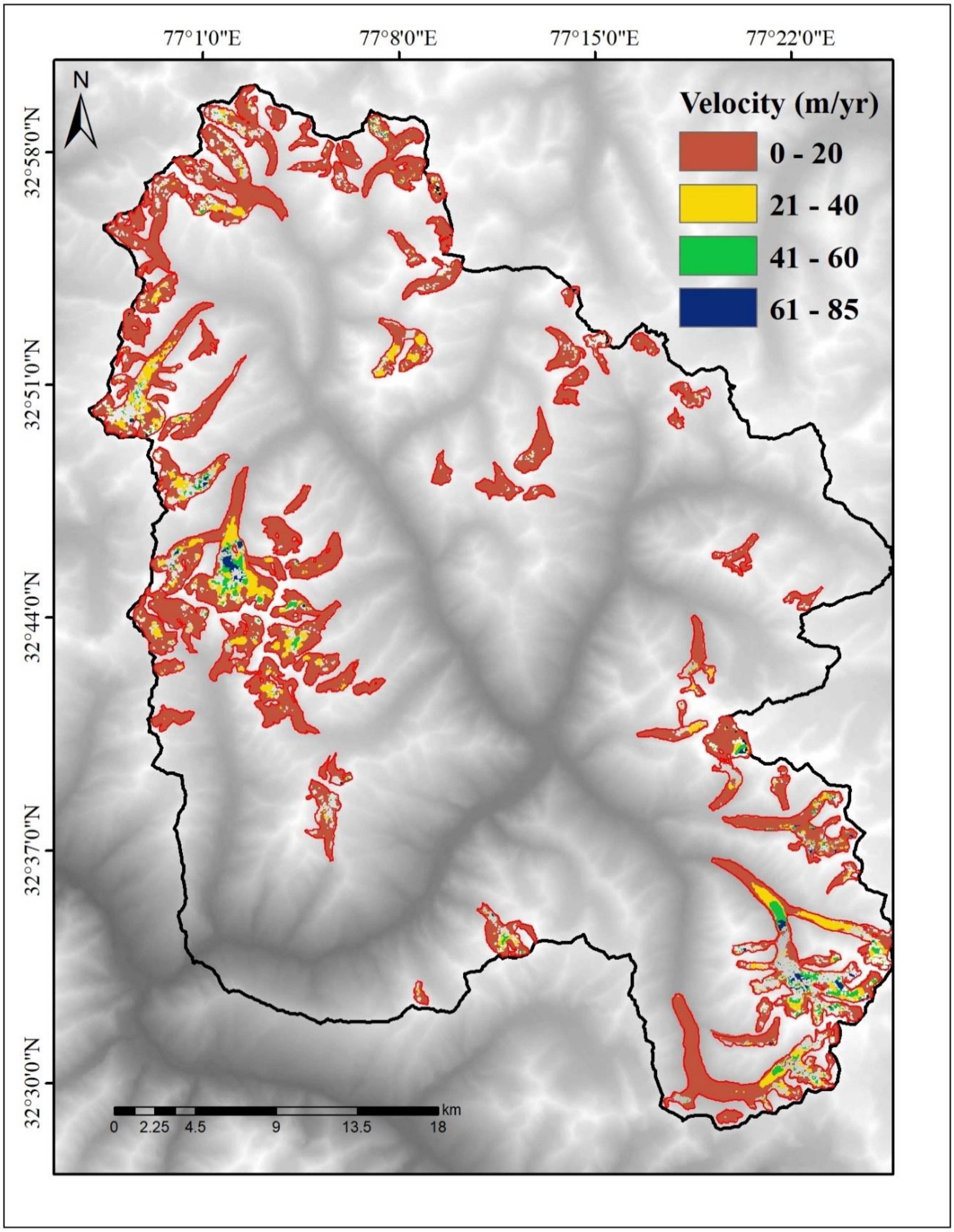


Figure 9. The map represents the spatial distribution of glacier surface velocity for individual glaciers in Bhaga basin. Larger glaciers were observed with greater mean surface velocity in the basin.

Table 3. Area, mean surface velocity and mean ice thickness of 64 glaciers in the Bhaga basin.

Glacier ID	Glacier area (Km^2)	Mean Velocity (myr^{-1})	Mean thickness (m)
6	4.3	11.0	40.9
8	1.0	5.2	35.4
9	1.0	3.5	30.5
40	0.9	4.2	37.3
41	1.6	8.2	49.7
44	3.5	7.7	49.4
46	4.1	7.3	63.7
67	1.1	5.9	38.4
72	1.7	5.9	28.0
73	0.5	5.5	35.1
76	1.5	8.7	31.0
86	1.9	6.6	34.1
88	1.1	5.5	47.5
97	1.1	9.9	61.2
102	1.3	5.4	43.5
103	1.3	5.9	43.7
109	1.6	8.3	51.5
110	0.9	5.8	39.5
112	6.8	8.3	47.3
114	1.0	4.6	44.8
116	6.0	9.1	74.4
119	13.3	8.7	53.7
127	8.8	6.3	60.8
133	1.3	8.6	40.2
136	1.4	6.7	38.9
138	3.0	6.6	57.5
153	5.0	14.1	59.9
154	0.6	6.9	37.8
162	2.5	6.5	57.6
168	3.2	8.0	54.2
169	0.8	6.0	36.9
170	2.3	6.0	45.3

173	1.1	5.5	29.0
180	2.4	10.5	47.7
185	1.4	5.7	35.7
187	9.0	12.2	67.5
191	3.1	9.6	46.4
195	6.2	10.7	64.1
203	27.4	19.5	68.4
205	1.0	7.9	50.6
218	2.7	9.8	39.2
219	1.9	4.4	49.4
222	1.3	5.0	37.7
225	15.8	13.6	82.1
233	3.5	8.9	49.8
235	5.1	8.3	62.0
236	21.2	18.2	73.5
238	1.0	8.9	36.6
240	1.7	5.6	42.6
242	6.2	16.5	68.7
243	4.1	9.1	64.1
245	0.8	4.0	45.5
247	2.7	5.7	52.6
249	2.6	9.6	43.5
250	6.9	8.4	48.9
251	8.0	11.4	58.5
255	5.3	8.3	56.6
271	1.0	9.6	35.8
288	0.6	10.4	27.7
300	1.0	5.9	29.9
302	2.1	8.4	45.1
303	0.8	4.3	29.0
305	17.3	10.7	78.7
307	0.3	4.3	31.8

4.3. SPATIAL DISTRIBUTION OF GLACIER ICE THICKNESS

Laminar flow method had applied to 64 glaciers in the basin whose glacier area is greater than 1 km^2, also satisfies the surface velocity estimates. The mean ice thickness of individual glaciers is given in Table 3. Mean ice thickness in the Bhaga basin was found to be ~48 m. Our estimates were showing that the range of ice thickness distribution was maximum in the central regions of the main trunk of the glaciers. For example, ice thickness attained a maximum of 450 m in the central part of the glacier no. 236. For the majority of the glaciers in the study area, thickness distribution varies between 100 - 200 m on the central main trunk of glaciers. At the snout, the mean thickness was estimated in the range of 16-71 m. The highest and lowest mean velocities were estimated for glacier no. 225 (~82 m) and glacier no. 288 (~28 m) respectively. The number of glaciers in different mean thickness range is shown in Figure 10. Majority of the glaciers (19 glaciers) in the basin having a mean thickness value between 40 - 50 m. The ice thickness distribution of individual glaciers in the Bhaga basin is shown in Figure 18.

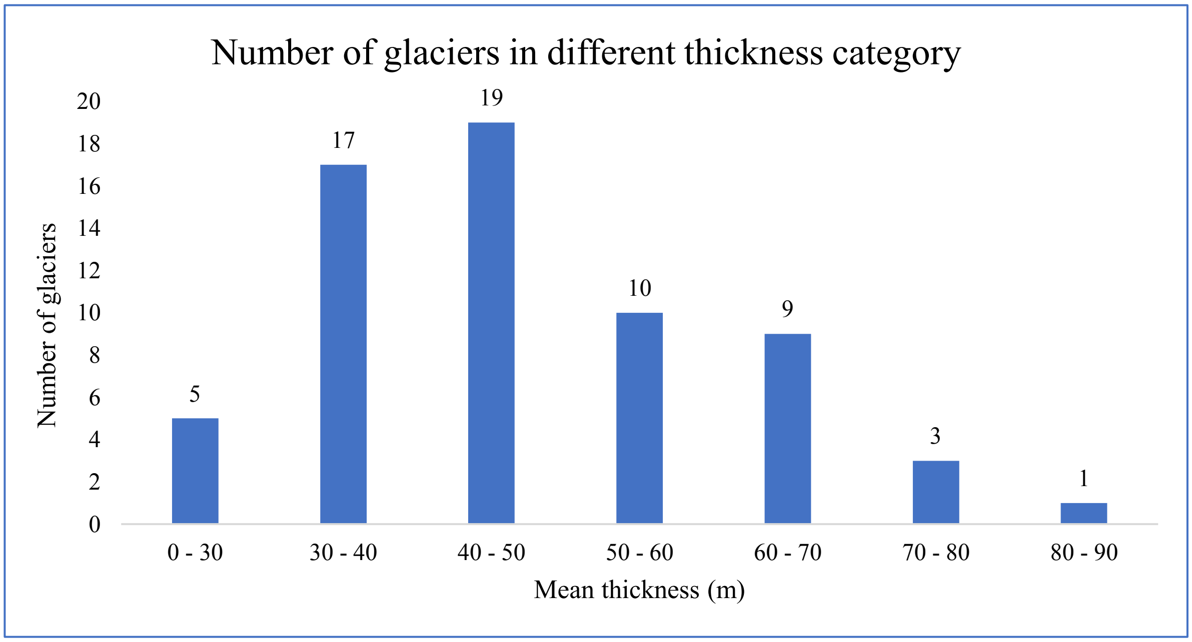


Figure 10. The histogram represents number of glaciers in different thickness range. Most of the glaciers in the basin having mean ice thickness value between 40-50 m.

Glacier surface velocity, modified glacier boundary, contour polygons, flowlines, and DEM are the input parameters required to run the HIGTHIM tool. Ice thickness distribution and bed topography are the outputs. As an example, the final surface velocity, velocity/displacement vectors, reclassified DEM (to create contour polygons), created contour polygons, glacier flowlines, ice thickness distribution, and bed topography images for the glacier no. 305 are given in Figure 11, 12, 13, 14, 15, 16 and 17 respectively.

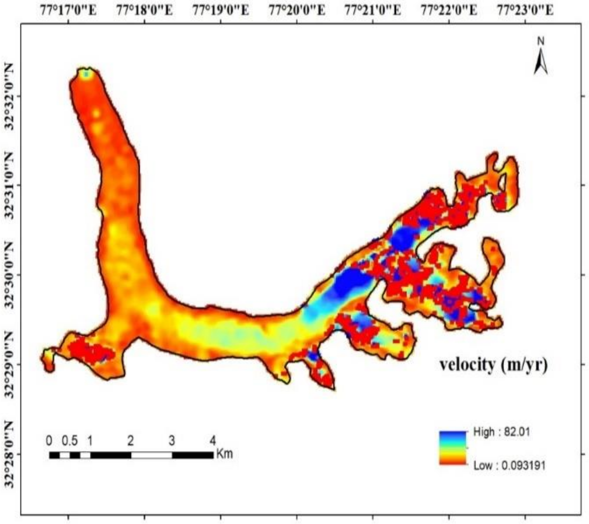


Figure 11. Final surface velocity of the glacier no. 305 estimated by subpixel correlation method. The color scale indicates the velocity range over the glacier.

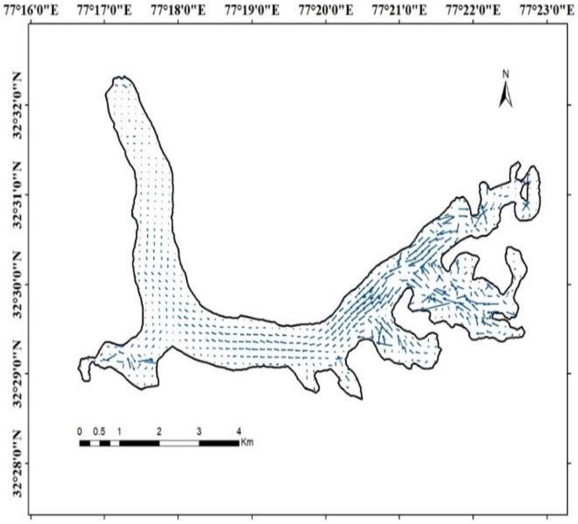


Figure 12. Velocity vector obtained for the glacier no. 305 after performing the subpixel correlation of landsat images for consecutive years.

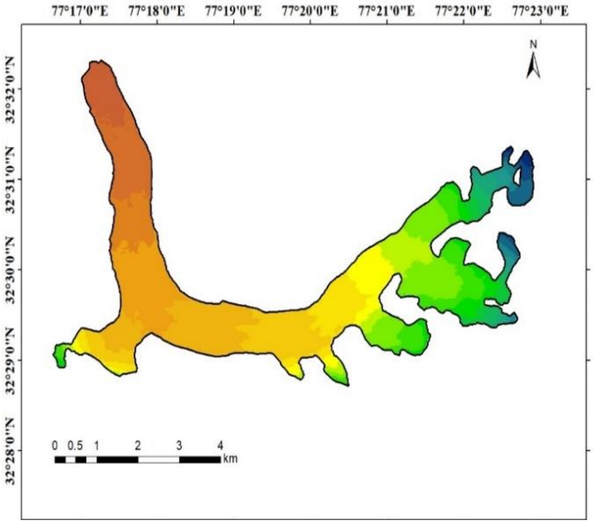


Figure 13. DEM reclassified with 100 m elevation classes for the glacier no. 305.

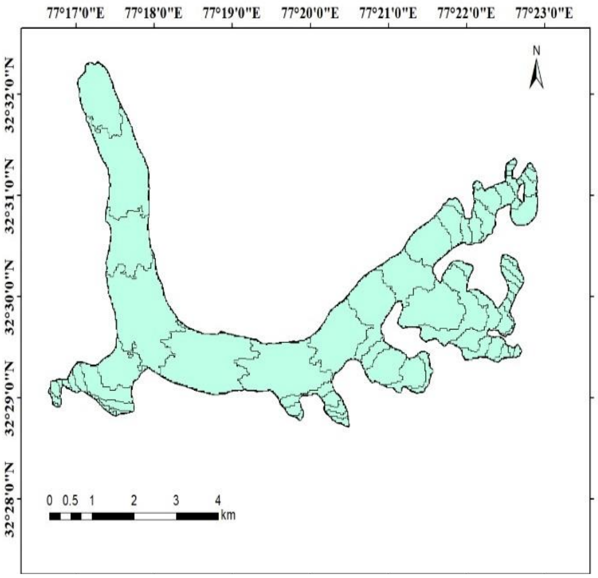


Figure 14. Created contour polygons for the glacier no. 305 from the reclassified DEM.

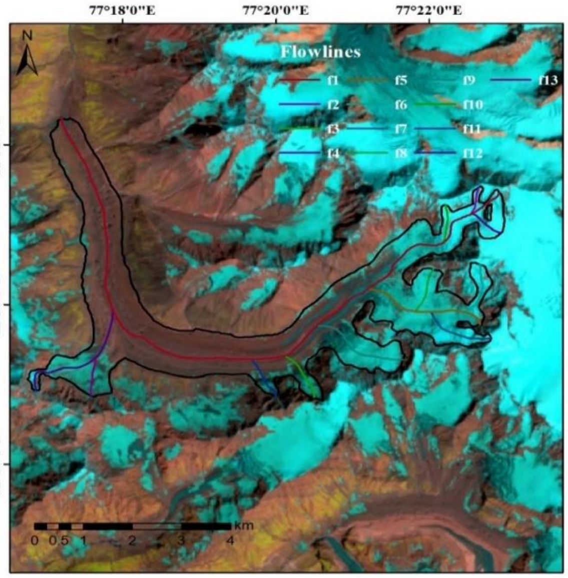


Figure 15. 13 flowlines are delineated for the glacier no. 305 including central flowline and tributary flowlines. Flowlines are digitized at 150m distance from the boundary. Each flowline is separated with 300-400 m.

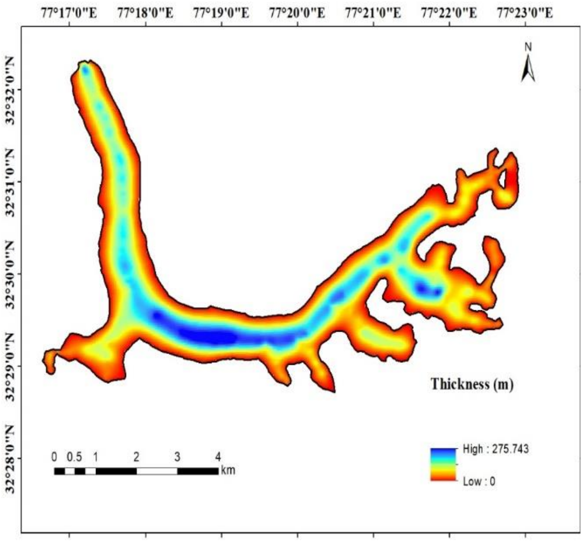


Figure 16. Distribution of ice thickness for the glacier no. 305. The thickness value is maximum at the central part of the main trunk and estimated mean thickness is ~79m.

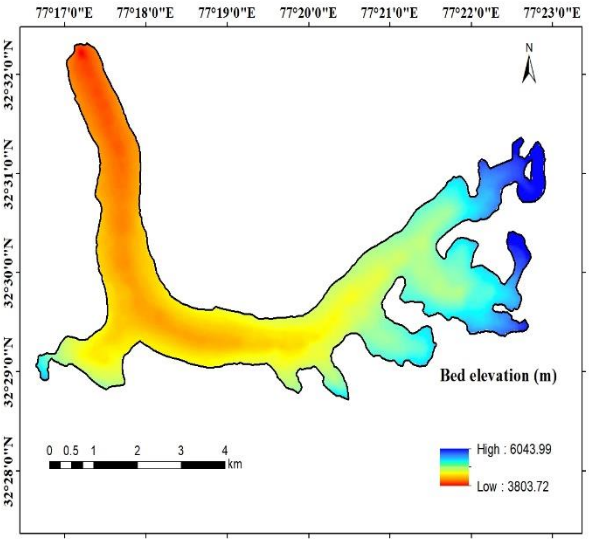


Figure 17. Topography of glacier bed for the glacier no. 305, having an elevation range of 3804 to 6044 m.

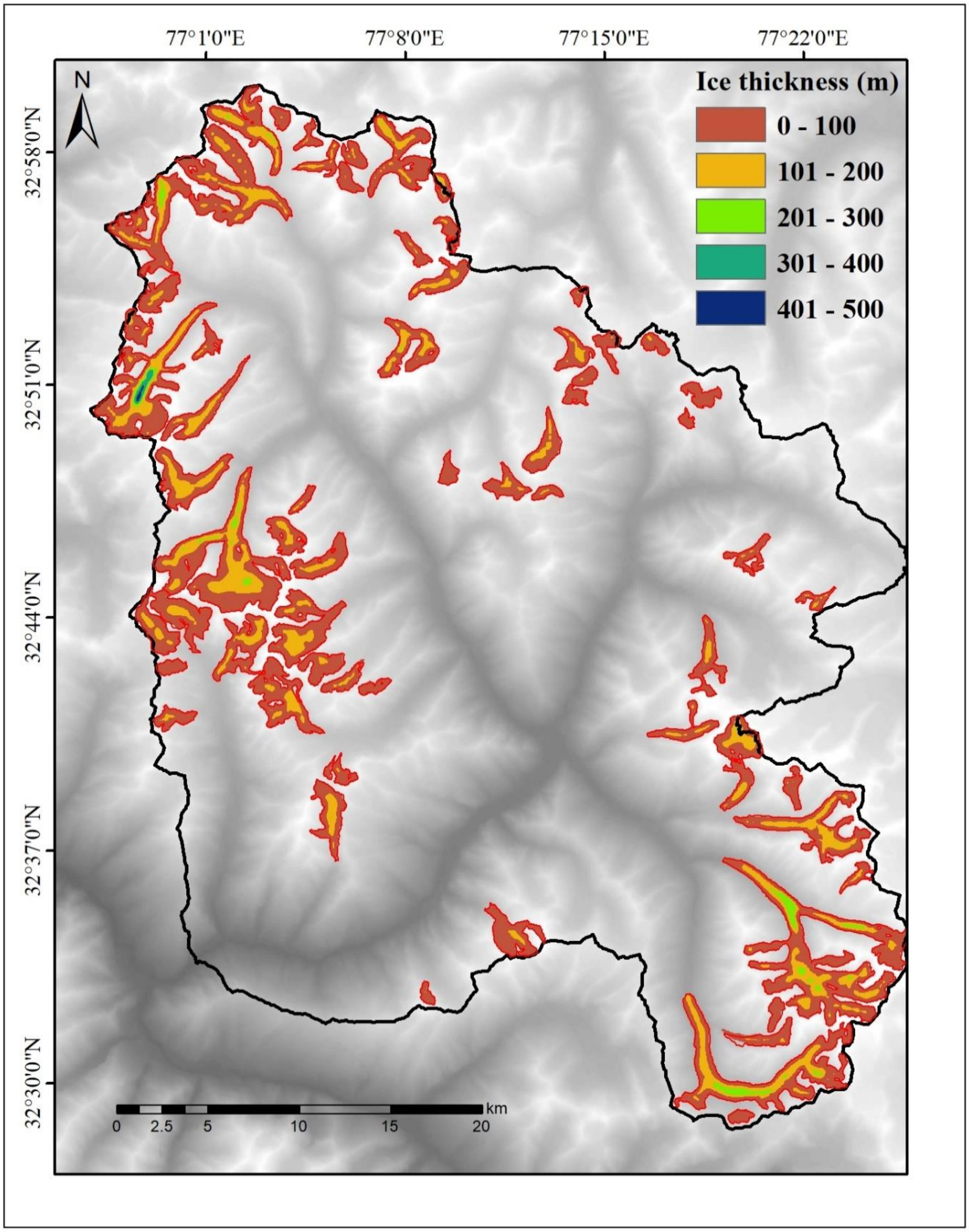


Figure 18. Spatial distribution of glacier ice thickness for individual glaciers in the Bhaga basin is shown in the map. Ice thickness distribution is maximum at the central part of the main trunk of the glaciers.

4.4. GLACIER STORED WATER IN THE BHAGA BASIN

For 64 glaciers, glacier volume was calculated from the estimated ice thickness. For the remaining glaciers, V-A scaling method was applied. A power law equation was computed using the 357 glaciers (area less than 10 sq. km) in the Bhaga basin along with the glaciers in Beas and Satluj river basins (Figure 19). The derived power law constant values are 0.033 (constant of proportionality ($\boldsymbol{C_A}$)) and 1.29 (scaling exponent ($\boldsymbol{\gamma}$)). Glacier volume for 255 glaciers was estimated using the following scaling equation:

$$\boldsymbol{V = 0.033 \times A^{1.29}}$$

where, **V** is the glacier ice volume (km^3) and **A** is the area of glacier (km^2).

The total ice volume in the Bhaga basin was estimated as ~17 km^3. Glacier stored water was calculated from this ice volume. Our estimate of total glacier stored water for 319 glaciers in the Bhaga basin is ~15 Gt. The spatial distribution of glacier stored water for individual glaciers is shown in Figure 20.

The estimated glacier stored water along with the glacier area for individual glaciers was tabulated in appendix I. Big blaciers were holding major part of the total water. About 66% of the total glacier volume (~10 Gt) was stored in large glaciers (area >5 sq. km), occupying a total area of ~161 km^2. The largest glacier (glacier no. 203, covering an area ~27 km^2) in the basin holds greatest amount of water (~2 Gt). About 91% of glaciers in the study area contains less than 0.1 Gt water in it.

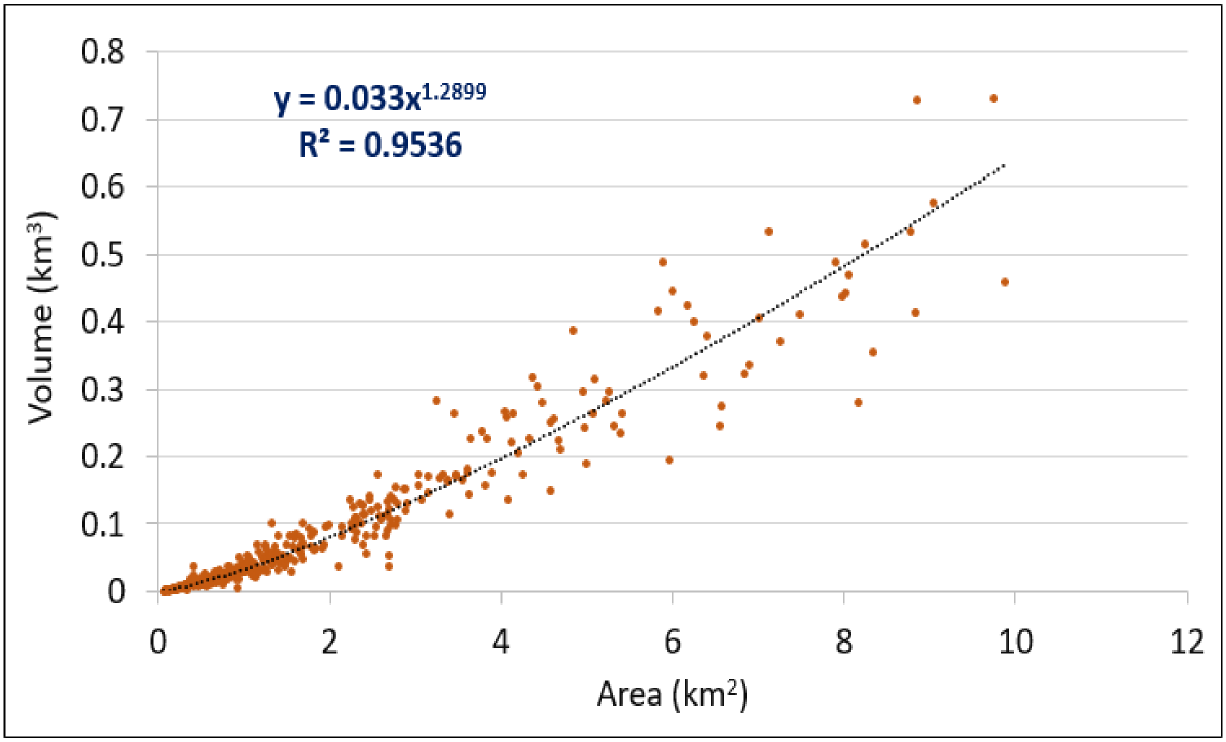


Figure 19. The scatter plot represents the Volume-Area relationship in Bhaga, Satluj and Beas basins. The relationship is formulated using 357 glaciers, whose areal extent is below 10 km^2.

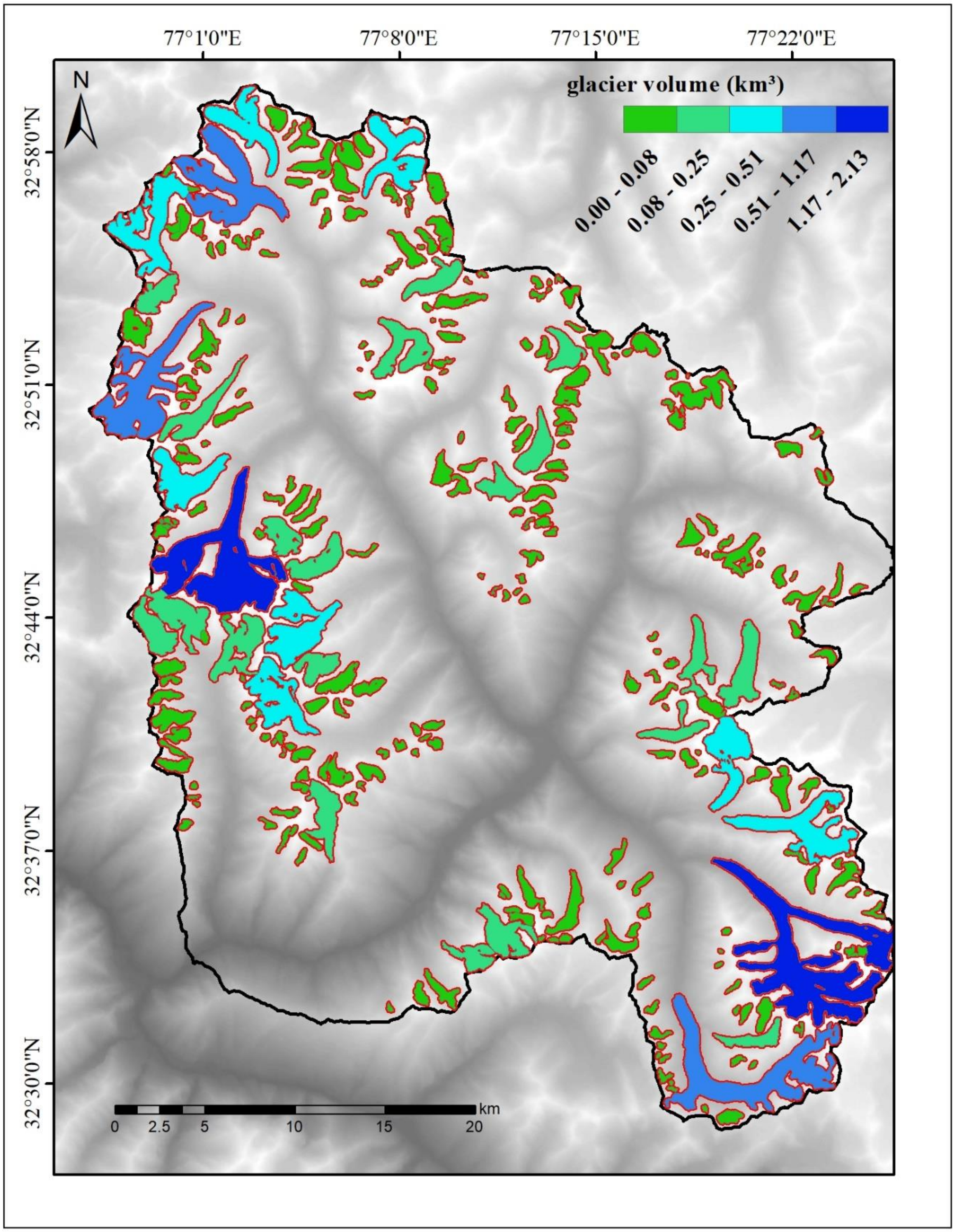


Figure 20. Spatial distribution of stored water in individual glaciers of the Bhaga basin. The total amount of glacier stored water in the Bhaga basin is 15.2 km^3.

4.5. POTENTIAL GLACIER LAKE SITES IN THE BHAGA BASIN

Glacier bed topography was estimated from the glacier depth and surface topography. Overdeepening of glacier lakes (for 28 glaciers) and their volume had been estimated using the bed topography (Figure 21). We have identified 84 potential lake sites. The total future lake volume and area was estimated as ~0.103 km^3 and ~584.6 ha respectively. The predicted glacier lake volume was maximum for the glacier no. 305 with a maximum predicted depth of ~189 m. The predicted potential glacier lake sites for the glacier no. 305 is given in Figure 22. This glacier has a modelled volume of 0.03 km^3 with an area of ~0.88 km^2. There is a large glacier lake present near the terminus of glacier no. 195. Predicted estimates of this glacier had shown a maximum depth of ~69 m also having a modelled volume of 0.01 km^3 with an area of ~0.45 km^2. Future expansion of this lake is showing in Figure 23. The total predicted area and volume of glacier lakes in the Bhaga basin are given in Table 4.

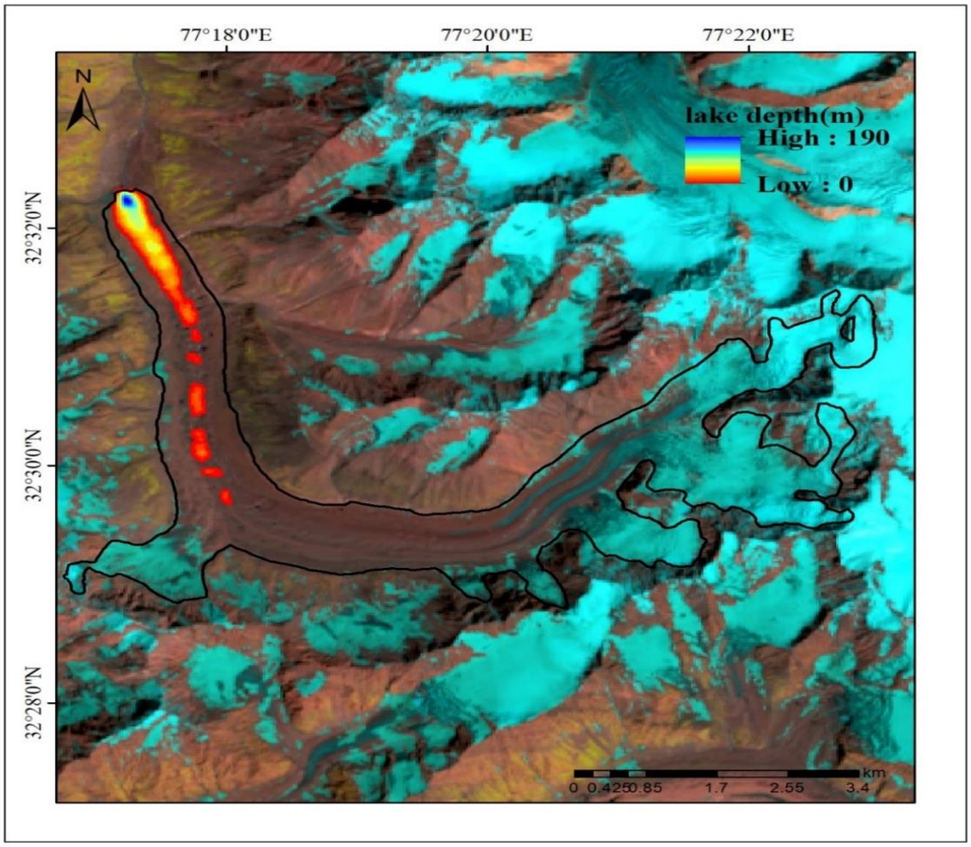


Figure 22. Lake sites predicted for the glacier no. 305 is shown in the map. The colour scale indicates the depth of predicted glacier lake.

Table 4. Future lake area and lake volume estimates for 28 glaciers in the study area

Glacier ID	Lake area (ha)	Lake volume (km^3)
40	2.57	0.0001
41	8.55	0.0012
44	7.81	0.0009
109	9.22	0.0015
112	22.76	0.003
116	43.77	0.009
119	31.06	0.008
138	12.54	0.0031
153	13.62	0.0013
162	12.38	0.0011
168	3.90	0.00007
169	2.57	0.0002
170	2.33	0.00007
180	3.65	0.0003
187	35.38	0.003
191	23.17	0.0016
195	43.61	0.01
203	52.41	0.008
225	30.98	0.0025
235	4.98	0.0003
236	51.16	0.008
242	9.05	0.0007
243	23.67	0.0042
249	7.97	0.0012
250	17.86	0.003
251	7.23	0.0005
255	11.96	0.0017
305	88.46	0.03

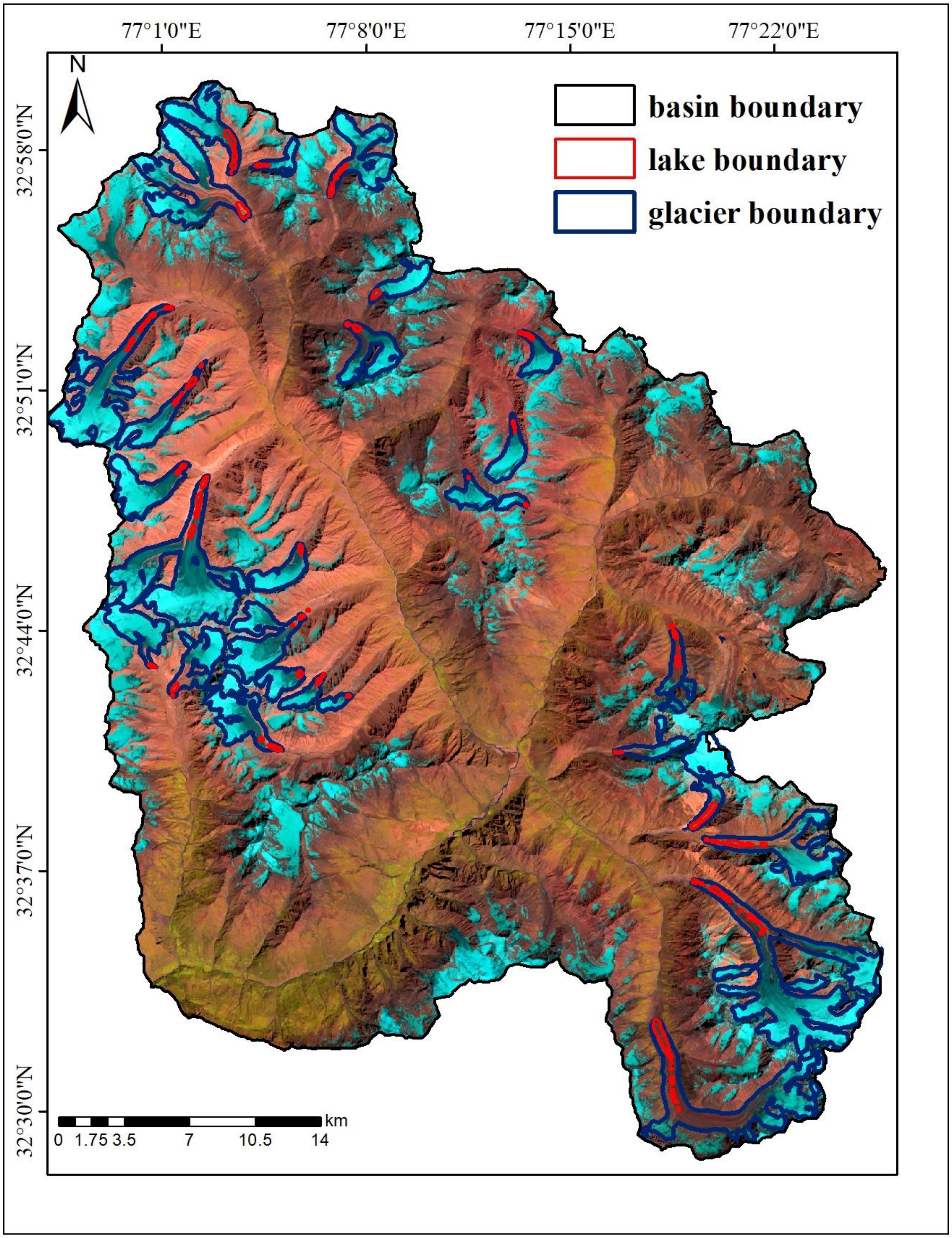


Figure 21. Map showing the potential lake sites predicted in the Bhaga basin. 84 future lake sites were identified and predicted lake boundaries are shown with red borders.

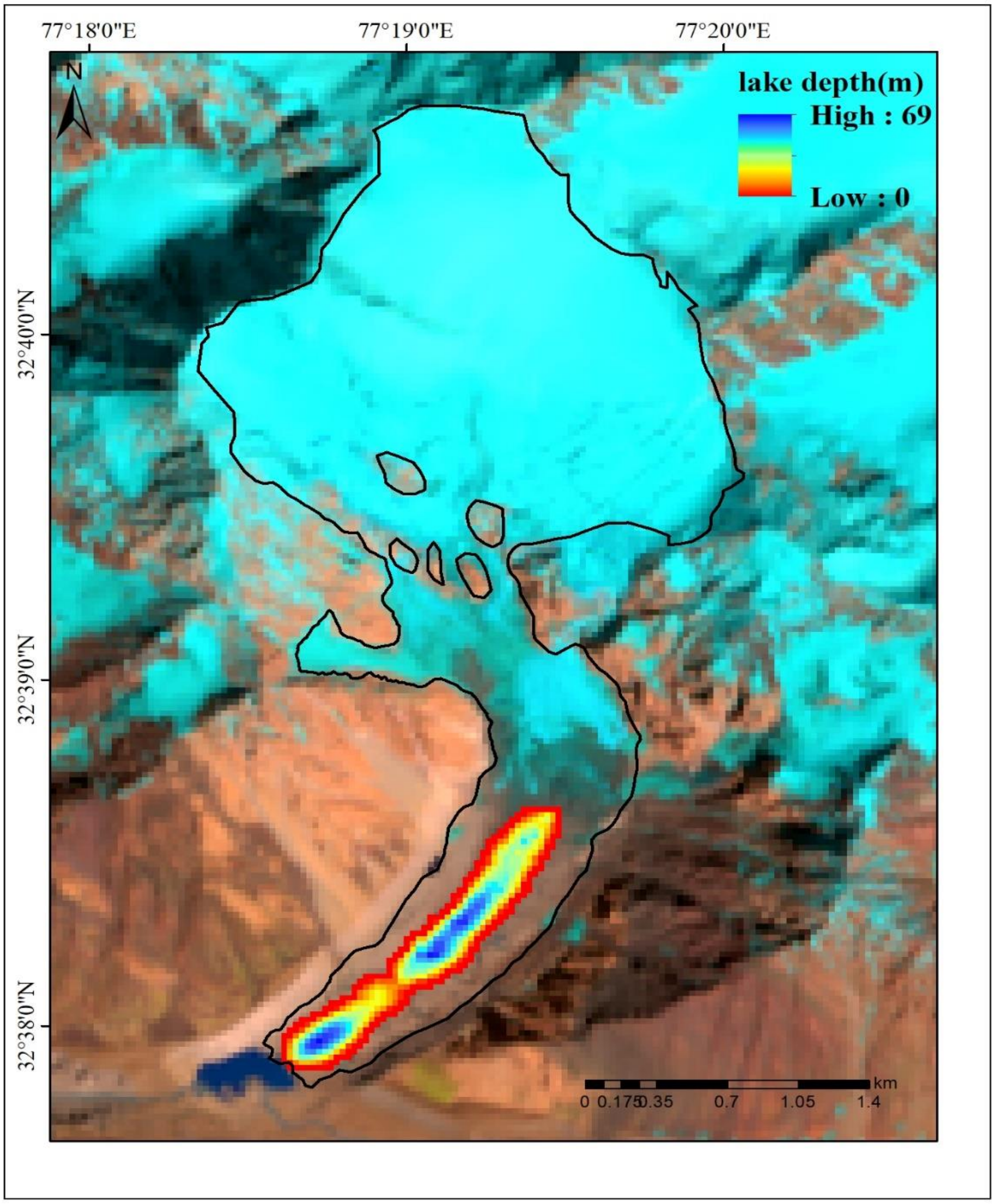


Figure 23. The future expansion of moraine dammed lake for the glacier no. 195 is shown in the map. Predicted lake area is 4.4 ha. Colour scale represents the predicted lake depth .

CHAPTER 5

DISCUSSION

5.1. GLACIER INVENTORY IN THE BHAGA BASIN

Remote sensing capabilities were used to identify and map individual glaciers precisely. Pandey and Venkataraman (2013) tested several methods (supervised classification, unsupervised classification, and NDSI methods) to delineate glaciers in the Chandra-Bhaga basin. The study conducted by Kaushik *et al.,* (2019) digitized clean ice glaciers in the Bhaga basin by adopting a hybrid semi-automated technique, which uses optical, thermal, and DEM (slope and elevation) data. These methods were useful on clean-ice glaciers only. That means it is quite challenging to delineate debris-covered glaciers using automatic as well as semi-automatic techniques. Manual delineation is more appropriate to apply in the case of such glaciers. Since most of the glaciers in the basin are debris-covered manual delineation methods were recommended for the Chandra-Bhaga basin. Therefore, we modified boundary manually using visual interpretation of satellite imagery.

Boundary modification changes glacier number, area, shape and other physiological features. The RGI glacier area was about 368 km^2. After modification, it was reduced to ~320 km^2. That means around 2% reduction was observed after modification. An investigation carried out by Nuimura *et al.,* (2015) stated that observed total area of glaciers in the Himalayan Karakoram region is less than RGI. However, the number of glaciers increased from 306 to 319. The RGI did not conduct a regional inventory of complex glacier structures and regional shrinkage information was not considering. Thus, the number of glaciers will be greater while examining glaciers on a regional scale (Pfeffer *et al.*, 2014). We also counted perennial snowfields as glaciers (as per Racoviteanu *et al.,* 2009). The use of satellite images for different time periods causes uncertainties in the glacier area (Nuimura *et al.,* 2015).

Birajdar *et al.,* (2014) conducted a multi-temporal digital glacier inventory on the Bhaga basin. The inventory concluding that the Bhaga basin consists of 231 glaciers with a glaciated area 385 km^2. This study considered glaciers having an area range between 0.03-29.28 km^2. Our present study had included glaciers below 0.03 km^2 area. This is one of the reasons for the difference in the glacier number between these two inventories. Another difference caused by the satellite data used for the inventory. Landsat 8 (OLI/TIRS) imagery for the years 2013 – 2019 were used in our study and previous inventory used IRS P6 LISS III images of 2001 and 2011.

Non-availability of snow and cloud-free satellite images and manual errors are the significant limitations during manual boundary modifications. However, it can conclude that a right glacier boundary is crucial for several glaciological studies such as depth and volume estimation and mass balance estimates.

5.2. SPATIAL DISTRIBUTION OF SURFACE VELOCITY

A significant difference in velocity between individual glaciers both spatially and temporally over the basin (Table 3) was observed in this study. It is due to topography, debris cover, slope, and shape of glaciers (Scherler *et al.,* 2011; Scherler *et al.,* 2008).

According to our estimates, glaciers in the Bhaga basin were moving with an annual mean velocity ~8.1 myr^{-1}. Das and Sharma (2019) also announced a similar velocity estimate (~8.4 myr^{-1}) for the glaciers in Jankar Chhu Watershed (JCW) (Part of Bhaga basin) between 2016 and 2017, using the COSI-Corr tool. The small differences in results are caused by the difference in spatial resolution and time of satellite images, snow and debris cover, etc. (Das and Sharma, 2019).

The individual glacier velocity of the current study showing that the largest glaciers were having the highest surface velocity. The largest glacier in the study area is glacier no. 203 (glaciated area ~27. km^2), which was having the highest mean surface velocity value (~19.5 myr^{-1}) (Figure 24) during the study period. A recent study conducted by Sun et al., (2017) also detected that big-sized glaciers move faster than the small glaciers. Another study conducted by Singh et al., (2020) also observed a positive correlation between glacier area and velocity for the glaciers in the Chandra-Bhaga sub-basins.

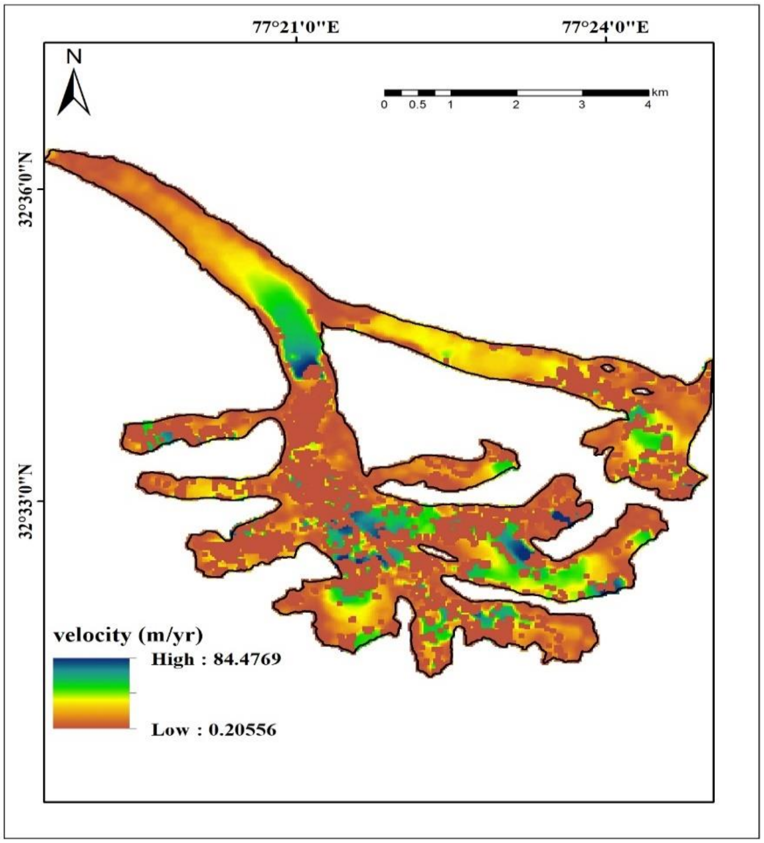


Figure 24. Spatial distribution of surface velocity for the glacier no. 203 (largest glacier in the Bhaga basin). The mean surface velocity ~19.5 myr^{-1}.

The glacier no. 119 (one of the largest glaciers in the Bhaga basin with a glacier area 13.3 km^2) having a mean velocity of 8.7 myr^{-1} which is considerably smaller value compared to other big glaciers (Figure 25). This glacier is characterized by a thick layer of debris over the glacier terminus and thin debris cover over the central part of the ablation area. Das and Sharma, (2019) estimated the surface velocity of this glacier as 7.4 myr^{-1}, analyzed the reason for this anomalous behavior is due to the presence of debris cover which retards the glacier movement.

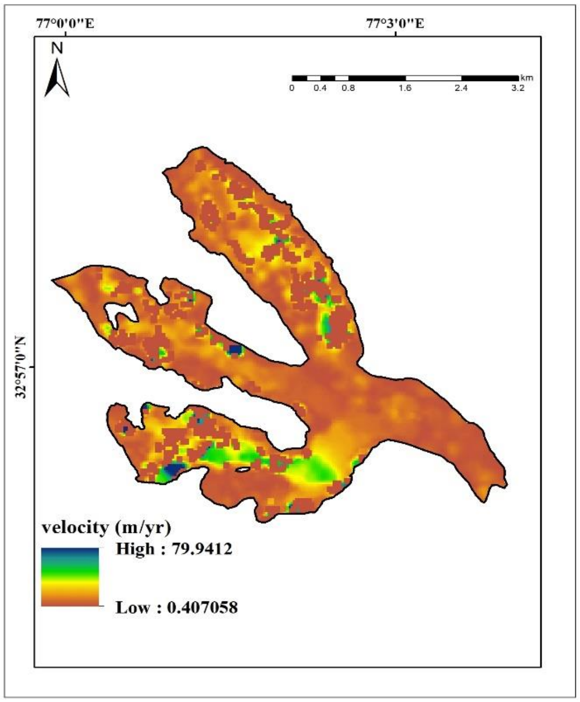


Figure 25. Surface velocity distribution of the glacier no. 119. Estimated mean velocity is ~8.7 myr^{-1}.

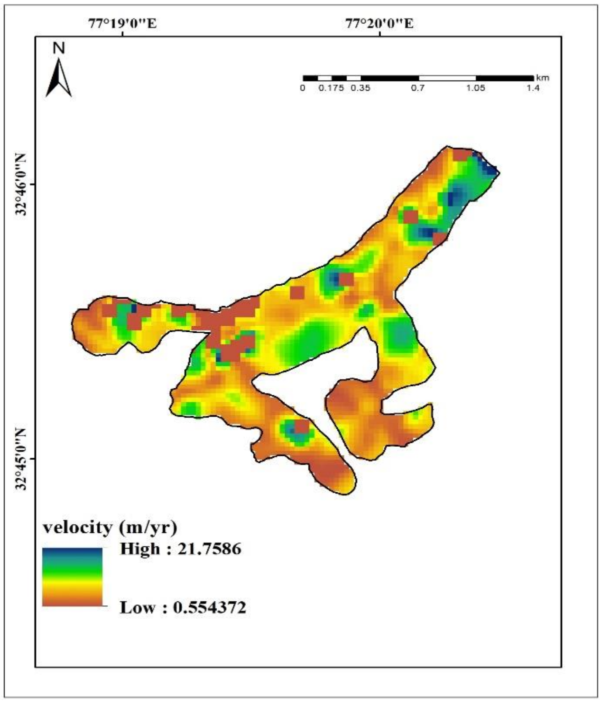


Figure 26. Surface velocity distribution map of Patseo glacier (glacier no.86). The mean velocity is estimated as ~8.7 myr^{-1}.

Singh et al., (2018) estimated the average surface velocity of the Patseo glacier (in the Bhaga basin) using the COSI-Corr technique as ~5.47 myr^{-1}. We estimated the mean surface velocity of Patseo glacier (glacier no.86) as ~6.6 myr^{-1} (Figure 26). The variation in estimation is caused by the difference in the spatial and temporal resolution of satellite images used in various studies. We had used Landsat 7/8 imageries for the boundary modification but Singh et al., (2018) used LISS IV satellite imagery.

Our analysis showing that the glaciers are moving faster in the accumulation area than the ablation area. Similar observations were reported by Singh et al., (2020) for the glaciers in the Chandra-Bhaga basins, Das and Sharma (2019) for JCW glaciers, and Gantayat et al., (2014) for Gangotri glacier.

The surface velocity can be used for glacier depth and stored water estimation. But the non-availability of good Landsat images, snow cover, cloud cover, and glacier melting create data gaps in the velocity estimation. This can be rectified by the use of good quality satellite images.

5.3. SPATIAL DISTRIBUTION OF GLACIER ICE THICKNESS

The laminar flow method uses the relation between surface velocity and slope. We estimated the mean ice thickness over the Bhaga basin as ~48m using this method. Frey *et al.,* (2014) had used a slope-dependent thickness estimation method for Western Himalayan glaciers (9760 glaciers). The estimated thickness value was between 58-79m. Since, Bhaga is one of the basins in Western Himalaya, the results from this paper can be comparable with our estimates. Local variations may occur while estimating the thickness regionally. Variations are also be caused by the difference in the number of glaciers had taken.

Our present observations showing that the distribution of ice thickness is maximum at the central region of the glacier main trunk than any other parts of the glacier (Figure 16). A study conducted by Gantayat *et al.,* (2014) over Gangotri glacier using the laminar flow method also presented similar observations. Other studies conducted by Singh et al., (2018) on the Patseo glacier and Ramasankaran et al., (2018) on Chhota shigri glacier were also supporting this observation. The maximum thickness over the central part of the main trunk is because of the highest mass contributions caused by the fastest glacier flow along with the central flowline. Contributions from the tributaries also maximize the thickness in the central main trunk (Ramasankaran et al., 2018).

A detailed analysis of our results showing that smaller glaciers can also attain large thickness values similar to the big glaciers (Table 3). Glacier no. 243 (area ~4.1 km^2; mean thickness ~64 m) (Figure 27) having a comparable mean thickness value with glacier no. 187 (area ~9 km^2; mean thickness ~67 m) (Figure 28). A study conducted by Pandit and Ramasankaran (2020) over Chandra basin glaciers was also observed a similar trend. i.e., glacier G4 (area ~6.56 km^2) in the Chandra basin having a mean thickness value ~131 m which is almost similar to the Bada Shigri glacier (area 136 km^2; mean thickness ~136 m).

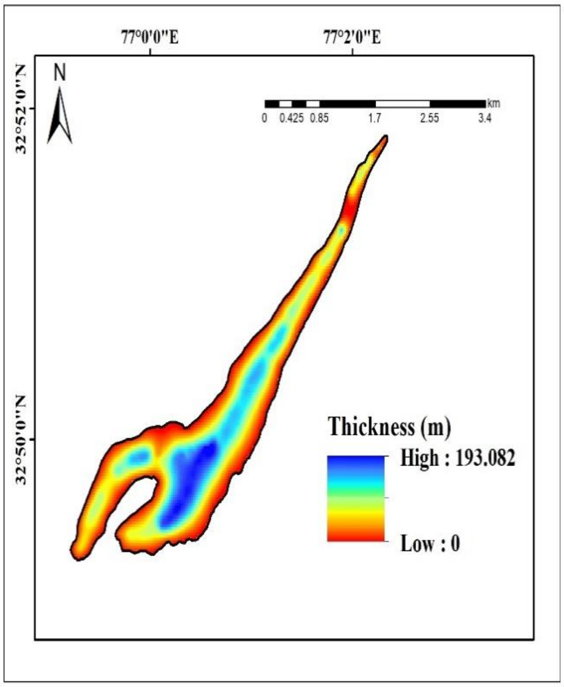


Figure 27. Ice thickness distribution of glacier no. 243. The estimated mean thickness is ~64m.

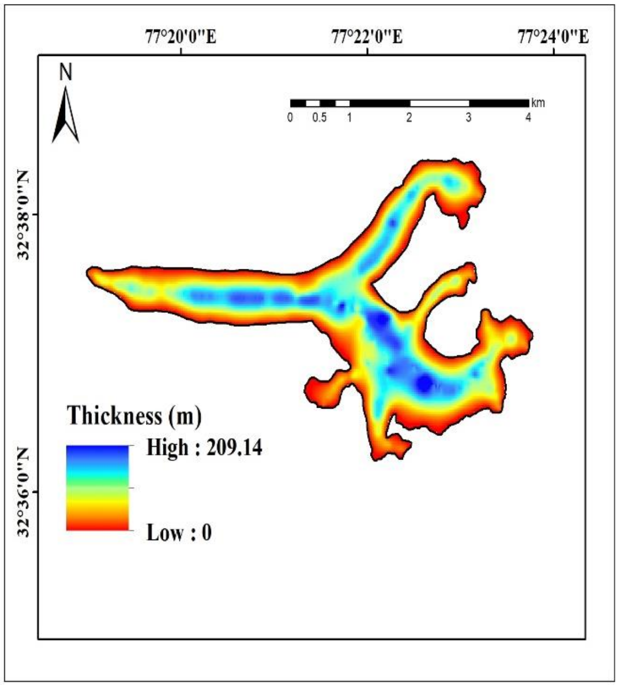


Figure 28. Distribution of ice thickness for glacier no. 187. The estimated mean thickness is ~67m.

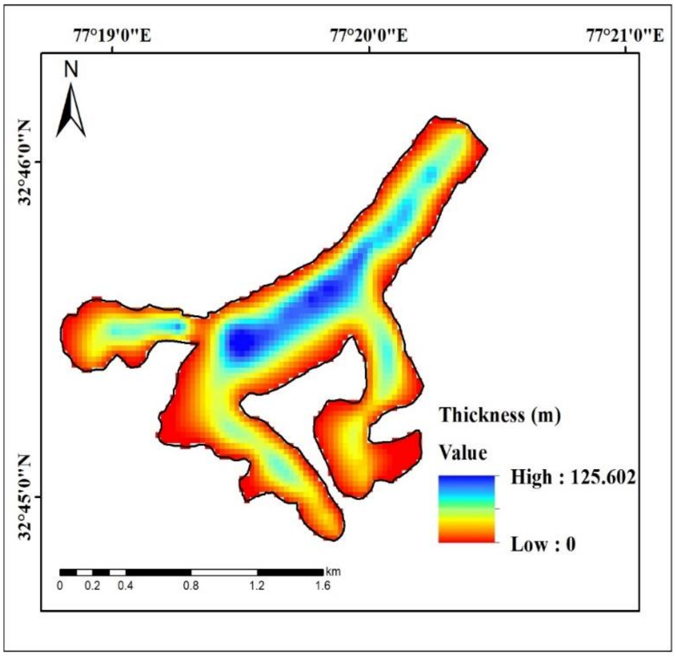


Figure 29. Spatial distribution of glacier ice thickness of Patseo glacier (glacier no. 86). The model estimated mean velocity is ~34 m.

In our present study, we had estimated the mean ice thickness of the Patseo glacier as ~34 m (Figure 29). Singh *et al.,* (2010) had estimated the depth range of the Patseo glacier using the GPR (Ground Penetrating Radar) technique as 33-42 m. These results are in good agreement with each other. Small variations are caused by the difference in thickness estimation method used. Laminar flow estimates give the spatial distribution of ice thickness. While the GPR technique gives point measurement results and it will not cover the entire glacier (Kulkarni *et al.,* 2017).

5.4. ESTIMATION OF GLACIER STORED WATER IN THE BHAGA BASIN

Singh *et al.,* (2019) (across the Karakoram region), Prasad *et al.,* (2019) (on Satluj basin), Pradeep *et al.,* (2018) (over the Sikkim Himalayan glaciers), Remya *et al.,* (2017) (on the Parbati basin), Pradeep *et al.,* (2017) (with the Spiti basin), and Gantayat *et al.,* (2014) (over the Gangotri glacier) had successfully applied the Laminar flow method across the Indian Himalayan region. Hence, we can say that our stored water estimation method is good enough to find out the glacier volume in the Bhaga basin. Meticulous measurement of stored water is very crucial in many climatological, hydrological, and sea-level studies.

The estimated ice thickness values were used for the stored water estimation in the Bhaga basin. We had estimated the total glacier stored water in the Bhaga basin as ~15 Gt.

Our volume estimates highlighting the importance of big glaciers in water storage. A lesser number of large glaciers (area greater than 5 km^2) can hold a huge amount (66 %) of water in it. At that same time, a large number of smaller glaciers stores only a very small part of the total glacier volume (about 91% of glaciers in the basin are smaller glaciers which stores only less than 0.1 km^3 water). Prasad *et al.,* (2019) observed a similar trend over the glaciers in the Satluj basin. In the Satluj basin, 56 % of the total volume is stored in bigger glaciers and ~95 % of the glaciers contains 0.1 Gt of ice. Another study conducted by Helfricht *et al.,* (2019) also stressed this imbalance between the number of glaciers, glacier area, and volume.

Our analysis showing that the stored water and glacier area are linearly related. The highest stored water value measured for the largest glacier in the basin. Glacier no. 203 (glacier area ~27.4 km^2) is the biggest glacier in the Bhaga basin, which holds ~2.1 km^3 (14% of the total volume) water in it. A similar proportionality between the glacier area and volume was observed by Helfricht *et al.,* (2019) over glaciers in Austria. Volume estimates of Prasad *et al.,* (2019) over the Satluj basin and Pandit and Ramasankaran (2020) over the Chandra basin also supported this observation.

5.5. POTENTIAL GLACIER LAKE SITES IN THE BHAGA BASIN

The formation and development of glacier lakes were closely associated with glacier dynamics. Glacier retreating results in the formation of new moraine-dammed or ice-dammed lakes as well as the growth of existing glacier lakes (Cook *et al.,* 2016; Raj and Kumar, 2016). In our present study, we had identified potential moraine-dammed lake sites and predicted their future expansion using the HIGTHIM tool. Only glacier lake areas greater than 0.01 km^2 were identified in our study.

We had identified a large moraine-dammed lake near the terminus of glacier no. 195. Our model predicted a large expansion of this lake in the future (Figure 23). A larger lake can create greater damage to the downstream valley since it can hold a large amount of water (Bolch *et al.,* 2011). Glacier lakes that are nourishing directly from meltwater (Wang *et al.,* 2013) and in contact with a glacier or near a glacier with steep slopes are more susceptible to outbursts (Prakash and Nagarajan, 2017a; 2017b). Thus, continuous monitoring of this lake is very urgent.

Our model estimates predicted 84 lake sites with a total area of ~585 ha over the Bhaga basin (Figure 21). An investigation by Prakash and Nagarajan (2017b) examined the glacier lakes over the Bhaga basin and identified 49 glacier lakes. Our investigation considered glacier lakes (moraine-dammed) having an area above 1 ha only. But the previous study detected and mapped present glacier lakes (landslide-dammed lakes, ice-dammed lakes, moraine-dammed lakes, and bedrock-dammed lakes) with an area greater than 0.1 ha using IRS-R-2 LISS IV 2011 images. Prakash and Nagarajan (2017b) considered only the existing lakes. But in our study, we had predicted the futue lake sites and expansion of the existing lakes.

In our present study, we had identified an increase in the number and area of glacier lakes in the future. We had observed very small glacier lakes over some glaciers. Glacier number 305 is one of the largest glaciers in the study area. Several tiny lakes were observed over the glacier trunk near the terminus. Our model results showing that the size of these existing lakes will increase in the future and new lakes will form over the glacier (Figure 17). A study conducted by Prakash and Nagarajan (2017a) and Prakash and Nagarajan (2017b) were also watched an increase in the number and area of glacier lakes across the North-western Himalayan region. The rapid increase in area and number of glacier lakes increases the risk of outburst floods (Prakash and Nagarajan, 2017b). The future coalesces of smaller lakes into a larger one amplifies this hazard risk. These abrupt changes are the results of global warming and will continue in the future (Bajracharya and Mool, 2009).

CHAPTER 6

SUMMARY AND CONCLUSION

The complex topography and diverse climate of the Himalaya affect the amount and seasonality of glacier melt. Meltwater from glaciers is one of the significant resources of the Himalayan rivers for sustaining the hydrological and socio-economic activities. Glacier retreat is one of the indicators of climate change over the Himalayan region. Increased temperature accelerates the melting, which further leads to the formation of moraine-dammed lakes. It can significantly influence the water security of the region. Quantification of stored water is essential to assess glacier health.

Numerous methods are used to estimate glacier volume. Field-based estimation is the conventional method. But it is an extreamly difficult process because of the rough Himalayan terrain and harsh climatic conditions. However, remote sensing capabilities can overcome this limitation. In our present study, we have focused on the estimation of the spatial distribution of glacier stored water in the Bhaga basin. Also, the identification of potentially dangerous glacier lake sites in the study area.

Glacier stored water over the Bhaga basin has been estimated using the laminar flow method, which utilises the relationship between glacier surface velocity, ice thickness and laminar flow of ice. The same method has been applied to predict potential glacier lake sites and expansion of existing lakes in the basin. To estimate the ice thickness distribution, we have used a semi-automated tool called Himalayan Glacier Thickness Mapper (HIGTHIM). The input parameters required for this tool are glacier boundary, surface velocity, contour ploygons, flowlines, moraines, and DEM (Digital Elevation Model). HIGTHIM tool gives spatial distribution of glacier ice thickness, glacier bed topography and predicted lake boundary as outputs. The surface velocity of glaciers is estimated using the sub-pixel correlation of Landsat images of consecutive years using COSI-Corr software. Other inputs were prepared using remote sensing tools such as Google Earth and ArcMap with the help of landsat images.

The salient findings are summarized as:

Around 319 glaciers were identified over the Bhaga basin. The total glaciated area is ~320 km^2. Around 20% of the basin is covered by glaciers.

In the Bhaga basin, the mean glacier surface velocity for 64 glaciers was estimated as ~8 myr^{-1}. This surface velocity had further used for the estimation of glacier ice thickness.

The glacier ice thickness along the flowline was estimated using the laminar flow equation. The mean glacier ice thickness for 64 glaciers in the Bhaga basin is ~48 m.

For that 64 glaciers, the glacier volume was estimated using this velocity-slope method. For the rest of the glaciers, the Volume-Area scaling method had applied. The total glacier stored water and total ice volume in the Bhaga basin were estimated as ~15 Gt and ~17 km^3 respectively.

The expansion of existing glacier lakes also predicted. The total predicted lake volume and area for 28 glaciers (84 lake sites) in the study area had been estimated as ~0.103 km^3 and ~585 ha respectively. Proper monitoring of glacier lakes is very necessary to avoid the occurrence of disasters.

Potential limitation:

Non-availability of good Landsat images is the major limitation of this study. It is quite difficult to find snow and cloud-free Landsat images. Accurate glacier boundary modification depends on the image quality. Precise boundaries are needed for area, velocity, thickness and stored water estimations. Lack of perfect (snow and cloud-free) Landsat images for consecutive year restricts velocity estimation over all the glaciers in the basin. Thickness estimation can only be carried out for those glaciers whose velocity fields were satisfied.

Future scope:

Any changes in glacier volume will, in turn, affect the glacier area. This will trigger the occurrence of disasters like glacier lake outburst floods, and landslides. Our results can be used to figure out the amount of water released after the bursting of moraine-dammed lakes. The timing of floodwater reaching the downstream can also calculate. Several models are now used for this estimations. Our results are beneficial to assess the potential of these hazardous events. In addition to this, the difficulties in various hydroelectric projects located downstream can be worked out. We can also practice our estimation methods over other basins in the Himalayas. Our results can be validated using field surveys.

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ESTIMATION OF GLACIER STORED WATER IN BHAGA BASIN, HIMALAYAS

by

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ABSTRACT

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ABSTRACT

Glaciers store huge amount of world's freshwater. Himalayan-Karakoram region is also prosperous due to its extensive glacier coverage. The melt runoff from Himalayan glaciers nourishes the rivers which helps to mountain community throughout the year. However, this is not a permanent source of water because the rise in temperature enhaces the speed of glacier retreat. Disappearing Himalayan glaciers reduces the seasonal waterflow over the basins. This inturn affects the natural systems. Thus, proper assessment of glacier volume is crucial to evaluate the water balance of river basins. Rapidly melting glaciers are very dangerous. They can develop lakes in the higher mountain regions depending upon the peri glacier geomorphology. When the glacier lake dams bursts, catastrophic floods occurs in downstream which sweeping away the villages lower down.

In the present study, we had estimated the glacier stored water for 319 glaciers (total area ~320 km^2) in the Bhaga basin using glacier surface velocity, slope, and laminar flow law. Also identified potential glacier lake sites in the Bhaga basin. Ice thickness distribution of glaciers were estimated using a semi-automated tool called Himalayan Glacier Thickness Mapper (HIGTHIM), which was developed based on the laminar flow law of ice. This python based tool requires glacier boundary, flowlines, moraine, surface velocity, Digital Elevation Models (DEMs), and contour polygons as the inputs parameters. It gives glacier ice thickness, bed topography, and predicted glacier lake boundary as the outputs.

The glacier boundaries were downloaded from the Randolph Glacier Inventory (Version 6.0) and then modified using the Landsat 7/8 imageries. The modified boundaries were further used for estimation of the spatial distribution of surface velocity, calculated by sub-pixel correlation of Landsat images of consecutive years using the COSI-Corr tool. DEM was downloaded from the USGS Earth Explorer website. Glacier flowlines and moraines were manual delineated over landssat images in a GIS environment (ArcMap tools). Contour polygons were created using DEM with the help of ArcGIS software.

After the modification of RGI boundaries, around 319 glaciers wer invented over the Bhaga basin having a total glaciated area ~320 km^2. The mean glacier surface velocity of 64 glaciers estimated as ~8.1 myr^{-1}. Most of the glaciers in the study area moving within a range of 5-10 myr^{-1}. The spatial distribution of glacier ice thickness and volume calculated for 64 glaciers using the laminar flow equation. For the remaining glaciers, V-A scaling method used. The mean glacier ice thickness and total stored water in the Bhaga basin were estimated as ~48 m and ~15 Gt respectively. We have identified 84 potential lake sites in the basin by estimating over deepening of bottom topography. The future expansion of existing glacier lakes also predicted. The total predicted lake volume of all glaciers estimated as ~0.103 km^3 , having a total lake area ~585 ha.

Millions of people living in the mountainous region depend on the water from glaciers for their livelihood. Therefore, it is necessary to have a proper estimate of the freshwater stored in glaciers. Continuous monitoring of glacier ice thickness and moraine-dammed lakes also important for planning mitigation measurements from disasters like glacier lake outburst floods (GLOFs). The laminar flow method has the potential to provide sufficient information to the policymakers for the preparation of mitigation strategies to secure life in the mountains.

APPENDIX I

GLACIER STORED WATER FOR INDIVIDUAL GLACIERS IN THE BHAGA BASIN ALONG WITH ITS AREA AND ICE VOLUME

Glacier ID	Glacier area (Km^2)	Ice Volume (Km^3)	Glacier stored water (Km^3)
1	0.169583	0.003345755	0.00301118
2	0.137801	0.002559974	0.002303977
3	0.088087	0.001437327	0.001293595
4	0.293756	0.006796261	0.006116635
5	0.299077	0.00695547	0.006259923
6	4.255285	0.213682526	0.192314273
7	1.113902	0.037926421	0.034133779
8	0.971986	0.031812411	0.02863117
9	0.981113	0.032198254	0.028978428
10	0.658805	0.019263201	0.017336881
11	0.322117	0.007654216	0.006888795
12	0.167411	0.003290583	0.002961525
13	0.389083	0.009765836	0.008789253
14	0.550847	0.015292194	0.013762975
15	0.529087	0.01451749	0.013065741
16	0.338531	0.008160992	0.007344893
17	0.13742	0.002550848	0.002295763
18	0.196892	0.004056381	0.003650743
19	0.069685	0.001062379	0.000956141
20	0.456845	0.012012954	0.010811659
21	0.110769	0.001931564	0.001738407
22	0.062643	0.000925976	0.000833379
23	0.14709	0.002784707	0.002506236
24	0.119746	0.002135811	0.00192223
25	0.086136	0.001396396	0.001256757
26	0.037857	0.000483576	0.000435218
27	0.326077	0.00777581	0.006998229
28	0.109243	0.001897308	0.001707577
29	0.061223	0.00089899	0.000809091
30	0.34014	0.00821106	0.007389954

31	0.362445	0.008912106	0.008020895
32	0.09665	0.00162004	0.001458036
33	0.309361	0.007265499	0.006538949
34	0.183792	0.003711665	0.003340499
35	0.771875	0.02362984	0.021266856
36	0.093348	0.001549004	0.001394103
37	0.239184	0.005213634	0.00469227
38	0.304329	0.007113421	0.006402079
39	0.078618	0.001241217	0.001117095
40	0.912675	0.029330924	0.026397832
41	1.58885	0.059964024	0.053967622
42	0.602666	0.017172553	0.015455298
43	0.313148	0.007380426	0.006642383
44	3.464506	0.163906915	0.147516223
45	0.392698	0.009883033	0.00889473
46	4.05838	0.20101483	0.180913347
47	0.404481	0.010267196	0.009240476
48	0.259207	0.005783315	0.005204984
49	0.053789	0.000760739	0.000684665
50	0.098639	0.001663173	0.001496855
51	0.917002	0.029510418	0.026559377
52	0.687918	0.020368193	0.018331373
53	0.065883	0.000988211	0.00088939
54	0.362318	0.008908078	0.00801727
55	0.3244	0.007724264	0.006951838
56	0.208293	0.004361867	0.00392568
57	0.081417	0.00129851	0.001168659
58	0.610949	0.017477598	0.015729838
59	0.076218	0.001192559	0.001073303
60	0.209286	0.004388708	0.003949837
61	0.419482	0.010760981	0.009684883
62	0.142257	0.002667249	0.002400525
63	0.145134	0.002737033	0.002463329
64	0.247241	0.005441267	0.004897141
65	0.775064	0.023755844	0.02138026
67	1.108246	0.037678199	0.033910379
68	0.123486	0.002222243	0.002000019
69	0.182518	0.003678512	0.003310661

70	0.198793	0.00410697	0.003696273
71	0.015233	0.000149448	0.000134503
72	1.678278	0.064352569	0.057917312
73	0.527249	0.01445247	0.013007223
74	1.337164	0.048004235	0.043203811
75	0.055601	0.000793955	0.00071456
76	1.494974	0.055433701	0.049890331
77	0.94987	0.030881825	0.027793642
78	0.351208	0.008557314	0.007701582
79	0.053301	0.000751848	0.000676663
80	0.0341	0.000422585	0.000380326
81	0.060686	0.000888832	0.000799949
82	0.053871	0.000762235	0.000686011
83	0.23059	0.004973268	0.004475941
84	0.517307	0.01410191	0.012691719
85	0.056479	0.000810164	0.000729148
86	1.90876	0.075972265	0.068375038
87	0.448122	0.011717905	0.010546115
88	1.053676	0.035302366	0.031772129
89	0.507484	0.013757459	0.012381713
90	0.308663	0.007244361	0.006519925
92	0.066873	0.001007407	0.000906666
93	0.035463	0.000444497	0.000400048
94	0.217979	0.004625248	0.004162723
95	0.038568	0.000495323	0.000445791
96	0.039382	0.000508849	0.000457964
97	1.146454	0.039362082	0.035425874
98	0.115041	0.002028186	0.001825367
99	0.04291	0.000568396	0.000511557
100	0.371212	0.00919114	0.008272026
101	0.029695	0.000353532	0.000318178
102	1.337843	0.04803568	0.043232112
103	1.2696	0.044898713	0.040408842
104	0.093442	0.001551016	0.001395914
105	0.525004	0.014373141	0.012935827
106	0.253571	0.005621627	0.005059464
107	0.324525	0.007728104	0.006955293
108	0.450391	0.011794494	0.010615044

109	1.592815	0.060157116	0.054141404
110	0.946124	0.03072482	0.027652338
111	0.14759	0.002796923	0.002517231
112	6.829757	0.393380904	0.354042814
113	0.719578	0.02158533	0.019426797
114	0.97433	0.031911404	0.028720263
115	0.146183	0.002762577	0.002486319
116	5.999586	0.332822427	0.299540184
117	0.086832	0.001410968	0.001269871
118	0.135601	0.002507378	0.00225664
119	13.315311	0.930710686	0.837639618
120	0.877244	0.027870512	0.025083461
121	0.348278	0.008465339	0.007618805
122	0.345644	0.008382847	0.007544562
123	0.164921	0.003227589	0.00290483
124	0.018213	0.000188183	0.000169365
125	0.210598	0.004424229	0.003981806
126	0.088219	0.001440106	0.001296096
127	8.777415	0.543704039	0.489333635
128	0.042741	0.00056551	0.000508959
129	0.050503	0.000701331	0.000631198
130	0.577055	0.016237083	0.014613375
131	0.045959	0.00062102	0.000558918
132	0.067358	0.001016841	0.000915157
133	1.279283	0.045340906	0.040806815
134	0.164782	0.00322408	0.002901672
135	0.044598	0.000597401	0.000537661
136	1.370383	0.049548029	0.044593227
137	0.131542	0.002410989	0.00216989
138	3.02609	0.137658625	0.123892762
139	0.11403	0.002005224	0.001804702
140	0.031715	0.000384853	0.000346368
141	0.095255	0.001589942	0.001430948
142	1.286228	0.045658662	0.041092795
143	0.169216	0.003336419	0.003002777
144	0.482774	0.012899568	0.011609611
145	0.025364	0.000288479	0.000259631
146	0.261382	0.005845987	0.005261388

147	0.049383	0.000681333	0.0006132
148	0.227011	0.004873925	0.004386532
149	0.010682	0.000169827	0.000152844
150	0.072754	0.001123112	0.001010801
151	0.279155	0.006363703	0.005727333
152	0.076348	0.001195184	0.001075665
153	4.962126	0.260528848	0.234475963
154	0.577904	0.016267904	0.014641114
155	0.038092	0.000487452	0.000438706
156	0.037091	0.000470992	0.000423893
157	0.208208	0.004359571	0.003923614
158	0.127341	0.002312131	0.002080918
159	0.033429	0.000411889	0.000370701
160	0.091476	0.001509051	0.001358146
161	0.196351	0.00404201	0.003637809
162	2.4595	0.105357938	0.094822144
163	0.498033	0.013427872	0.012085085
164	0.204753	0.004266482	0.003839833
166	0.478391	0.012748704	0.011473833
167	0.566354	0.015849739	0.014264765
168	3.151413	0.145056086	0.130550477
169	0.838102	0.026276927	0.023649235
170	2.25343	0.094112543	0.084701289
171	0.343166	0.008305406	0.007474866
172	0.541226	0.01494855	0.013453695
173	1.13481	0.038847164	0.034962447
174	0.061118	0.000897002	0.000807302
175	0.054806	0.000779342	0.000701408
176	0.220506	0.004694528	0.004225075
177	0.166901	0.003277659	0.002949893
178	0.444407	0.011592751	0.010433476
179	0.048527	0.000666138	0.000599524
180	2.384202	0.101215899	0.091094309
181	0.035783	0.000449678	0.00040471
182	0.483978	0.01294108	0.011646972
183	0.152807	0.002925097	0.002632588
184	0.485119	0.012980447	0.011682402
185	1.352602	0.048720323	0.04384829

186	0.474299	0.012608217	0.011347396
187	9.048278	0.565442359	0.508898123
188	0.075756	0.001183243	0.001064919
189	0.027191	0.000315558	0.000284002
190	0.428966	0.011075828	0.009968245
191	3.147096	0.144799825	0.130319843
192	4.832759	0.251800883	0.226620795
194	0.966549	0.031583061	0.028424755
195	6.248328	0.350727396	0.315654656
196	0.181654	0.003656066	0.003290459
197	0.123803	0.002229605	0.002006644
198	0.120878	0.00216189	0.001945701
199	0.572887	0.016085964	0.014477368
200	0.185947	0.003767897	0.003391107
201	0.33764	0.008133297	0.007319967
203	27.39919	2.360759957	2.124683961
204	0.157395	0.003038873	0.002734986
205	1.036551	0.034564028	0.031107625
206	0.055845	0.000798452	0.000718607
208	0.050138	0.000694799	0.000625319
209	0.218117	0.004629025	0.004166123
210	0.093117	0.001544061	0.001389655
211	0.16837	0.003314918	0.002983426
212	0.035537	0.000445694	0.000401125
213	0.074019	0.001148364	0.001033528
214	0.091365	0.00150669	0.001356021
215	0.216014	0.004571536	0.004114382
216	0.034788	0.000433615	0.000390253
217	0.099404	0.001679829	0.001511846
218	2.710543	0.119429953	0.107486958
219	1.949122	0.078050789	0.07024571
220	0.19728	0.004066695	0.003660025
221	0.092875	0.001538887	0.001384998
222	1.286334	0.045663515	0.041097164
223	0.523804	0.014330779	0.012897701
224	0.303002	0.007073437	0.006366093
225	13.836653	0.977979814	0.880181833
226	0.845824	0.026589638	0.023930674

227	0.744061	0.022537295	0.020283566
228	0.317341	0.007508144	0.006757329
229	0.069998	0.001068538	0.000961684
230	0.029379	0.000348686	0.000313818
231	0.175842	0.003505884	0.003155296
232	0.286939	0.006593511	0.00593416
233	3.478085	0.164736052	0.148262447
234	0.246417	0.005417887	0.004876098
235	5.091258	0.269307001	0.242376301
236	21.245026	1.700368647	1.530331782
237	0.330243	0.007904191	0.007113772
238	1.036676	0.034569405	0.031112464
239	0.739469	0.022358044	0.02012224
240	1.66178	0.063537736	0.057183962
242	6.172183	0.345223968	0.310701571
243	4.129124	0.205546023	0.18499142
244	0.198319	0.004094343	0.003684908
245	0.804713	0.024934478	0.022441031
246	0.171554	0.003395999	0.003056399
247	2.705561	0.119146879	0.107232191
248	0.554826	0.015434828	0.013891345
249	2.570334	0.111521724	0.100369552
250	6.894713	0.398213498	0.358392148
251	8.048518	0.486179793	0.437561814
253	0.603467	0.017201999	0.015481799
255	5.251121	0.280263814	0.252237433
256	0.094063	0.001564325	0.001407892
256	0.094063	0.001564325	0.001407892
257	0.057581	0.000830612	0.000747551
258	0.12915	0.002354586	0.002119128
259	0.051822	0.000725046	0.000652542
260	0.103369	0.001766754	0.001590078
261	0.059329	0.000863279	0.000776951
262	0.128408	0.002337152	0.002103436
263	0.030237	0.000361877	0.000325689
264	0.055874	0.000798987	0.000719088
265	0.126831	0.002300194	0.002070174
266	0.210367	0.00441797	0.003976173

267	0.579682	0.016332493	0.014699244
268	0.315392	0.007448716	0.006703845
269	0.221141	0.004711973	0.004240776
270	0.404794	0.010277445	0.009249701
271	1.036263	0.034551641	0.031096477
274	0.166136	0.003258293	0.002932464
275	0.236928	0.005150289	0.00463526
276	0.138924	0.002586916	0.002328225
277	0.149959	0.002854966	0.002569469
278	2.041277	0.082843122	0.074558809
279	0.207108	0.004329884	0.003896896
280	1.109748	0.037744081	0.033969673
281	0.193517	0.003966915	0.003570224
282	0.135254	0.002499105	0.002249194
283	0.242877	0.0053177	0.00478593
284	0.237669	0.005171076	0.004653968
285	0.372445	0.009230538	0.008307484
286	0.170949	0.003380559	0.003042503
287	0.105883	0.001822373	0.001640136
288	0.608419	0.017384295	0.015645866
289	0.103974	0.001780103	0.001602093
290	0.220126	0.004684095	0.004215686
291	0.091539	0.001510392	0.001359353
292	0.271701	0.006145373	0.005530835
293	0.047079	0.00064061	0.000576549
294	0.124935	0.002255936	0.002030342
295	0.066986	0.001009603	0.000908643
296	2.30657	0.096985008	0.087286508
297	1.181036	0.040900268	0.036810242
298	0.09626	0.001611613	0.001450452
299	0.352474	0.008597124	0.007737411
300	1.016261	0.033693802	0.030324422
301	0.177601	0.003551187	0.003196069
302	2.142627	0.088186463	0.079367817
303	0.773028	0.02367538	0.021307842
304	0.085903	0.001391526	0.001252373
305	17.284	1.303020558	1.172718502
306	0.059957	0.000875084	0.000787575

307	0.3177	0.007519101	0.006767191
308	0.100759	0.001709424	0.001538482
309	0.093469	0.001551594	0.001396435
310	0.373341	0.009259191	0.008333272
311	0.301139	0.007017388	0.006315649
312	0.099054	0.001672204	0.001504984
313	0.559721	0.015610705	0.014049634
314	0.259582	0.00579411	0.005214699
315	0.10912	0.001894553	0.001705098
316	0.041686	0.00054757	0.000492813
317	0.08638	0.001401501	0.001261351
318	0.033117	0.000406937	0.000366244
319	0.032015	0.000389556	0.0003506
320	0.03044	0.000365014	0.000328512
321	0.025283	0.000287291	0.000258562
322	0.064307	0.000957825	0.000862043
323	0.147751	0.002800859	0.002520773
324	0.035842	0.000450635	0.000405571
325	0.044787	0.000600669	0.000540602
326	0.036876	0.000467473	0.000420726
327	0.019658	0.000207659	0.000186893
328	0.022342	0.000244933	0.000220439
329	0.036243	0.000457148	0.000411434