PRELIMINARY STUDIES ON GEOMORPHOLOGY AND MASS CHANGE OF MULKILA GLACIER, HIMACHAL PRADESH USING GEOSPATIAL APPROACHES

Dissertation submitted to
Jawaharlal Nehru University
in partial fulfilment of the requirements
for the award of degree of

MASTER OF PHILOSOPHY

SARVAGYA VATSAL

School of Environmental Sciences
Jawaharlal Nehru University
New Delhi- 110067

2017

जवाहरलाल नेहरू विश्वविद्यालय
Jawaharlal Nehru University
SCHOOL OF ENVIRONMENTAL SCIENCES
New Delhi-110067
Tele. 011-26704303, 4304

CERTIFICATE

This is to certify that the research work embodied in this dissertation entitled **"Preliminary studies on geomorphology and mass change of Mulkila glacier, Himachal Pradesh using geospatial approaches"** has been carried out in the School of Environmental Sciences, Jawaharlal Nehru University, New Delhi. This work is original and has not been submitted in part or full for any other degree or diploma to any other University.

Sarvagya Vatsal
(Candidate)

Prof. Saumitra Mukherjee
(Dean)

प्रो.सौमित्र मुखर्जी / Prof. S. Mukherjee
डीन / Dean
पर्यावरण विज्ञान संस्थान
School of Environmental Sciences
जवाहरलाल नेहरू विश्वविद्यालय,
Jawaharlal Nehru University
नई दिल्ली-110067/New Delhi-110067

Prof. AL. Ramanathan
(Supervisor)

Acknowledgements

First and foremost I would like to offer my sincerest gratitude to my supervisor, Prof. AL. Ramanathan, who has supported me throughout my dissertation with his patience and knowledge whilst allowing me to work in the lab in my own way. Without his untiring supervision, invaluable suggestions and inspiring guidance, it would not have been possible to bring this work into its present shape. I would also like to offer my gratitude to Dr. Ishmohan Bahuguna Scientist and Head, Cryosphere Science Division (CSD), Space Application Center (SAC), ISRO, Ahmedabad who supported me during my M.Phil. and permitted to work in his lab.

I am deeply grateful to Prof. Saumitra Mukherjee (Dean), for providing me necessary facilities in time, so that this work could be completed in due course of time. I also thank all the faculty members of School of Environmental Sciences for their kind support during my research work. All the Staff of SES deserve due credit for their support directly or indirectly throughout this study.

I am thankful to Thupstan Angchuk, Som Dutt Mishra for their support and cooperation throughout the field work. The support and assistance from my lab mates, Shyam sir, Manish sir, Soheb sir, Rahul sir, Shailesh sir, Arindan sir, Naveen sir, Prabhat sir, Namrata mam, Karuna mam, Om sir, Monika, Chatterjee Dada, Ravi and Bhim deserves a special mention for their constant support and encouragement. I am also grateful to SAC, ISRO, Ahmedabad for providing me financial support for research work, since financial aid is always amongst the prerequisites for a research venture.

Apart from these I am thankful to some of my friends and seniors Chandu sir, Harshita mam, Madhvi mam, Saumya G kutty, Sumeet sir, Abhishek Bhai Sahab, Praveen, Saurabh, Arjit, Deepak, Vishal and Shailendra for their ceaseless efforts in boosting me up during the course of my research work.

With due respect, I would like to thank my entire family for their care and cooperation in letting me finish this dissertation work without any interruption.

Sarvagya Vatsal

Contents

List of figures

List of Tables

Chapter 1

INTRODUCTION

Mountain glaciers and ice caps are crucial evidences of the effect of climate change. The Intergovernmental Panel on Climate Change (IPCC) has recognized their importance as an overall temperature indicator and included the data of glacier fluctuation in all of their assessments since 1990 (Houghton et al., 2001). Glacier melt is responsible for sea level rise. 15-20 % of rise in eustatic sea level has been reported (Dyurgerov and Meier, 1997). There is an increase in literature on the changes happened in glacier after the maximum of little ice age (Luckman and Villalba, 2001; Solomina, 2000) and in the second half of twentieth century focusing mainly on snout monitoring and the mass balance of the glaciers. While it has been observed that glaciers which lie in low altitude regions are retreating with a faster rate (Williams and Ferrigno, 2012) and many more studies suggest that the rate of retreat is accelerated since the late 1970s mainly in two regions i.e. European Alps and Alaska (Dyurgerov and Meier, 1999; Arendt et al., 2006; Meier and Dyurgerov, 2003). In the Patagonian Ice field, it has been reported that mass loss has increased approximately two times from late 1970s (Rignot et al., 2003).

On the global level, highest glaciated area is Arctic island followed by Antarctica. The glacier distribution (% area) around the world is described by Table 1 below.

Table 1.1- Region wise glacier area (Dyurgerov & Meier, 1997)

Region	**Glacier area (%)**
Arctic island	35
Glacier and ice caps around Greenland and Antarctica	21
Asia	18
Alaska	1
Other USA- Canada	7
South America, New Zealand, Subarctic island	5
Europe	3

In Asia, the Himalayas are the major mountain chains which provide platform for many glaciers. Himalayan Glaciers are considered the third pole of the Earth's Cryosphere (Bahadur, 1993**)** as these are the most important reservoirs of fresh ice mass and consequently freshwater, after the polar regions (Hefner, 2016). A total of 9575 glaciers have been recorded in the Indian Himalayan region comprising a cumulative area of around 37,466 km^2 (Sangewar et al., 2009). These glaciers have a large socio-economic impact on human societies (Pant, 1988). River systems in the Himalayas which serve as the source of freshwater for more than 1.5 billion people in their catchment area include the Ganges, Brahamputra, Indus, Yangtez and Yellow river (Immerzeel et al., 2010). The Himalayas are therefore, also known as the water tower of Asia (Xu et al., 2009). This necessitates extensive scientific studies on the Himalayan glaciers, their dynamics and role in global climate change. Various studies have been conducted on different glacier systems around the world and most of them have reported a retreat of the glacier (Oerlemans, 2005; Raup et al., 2007; Solomina et al., 2008).

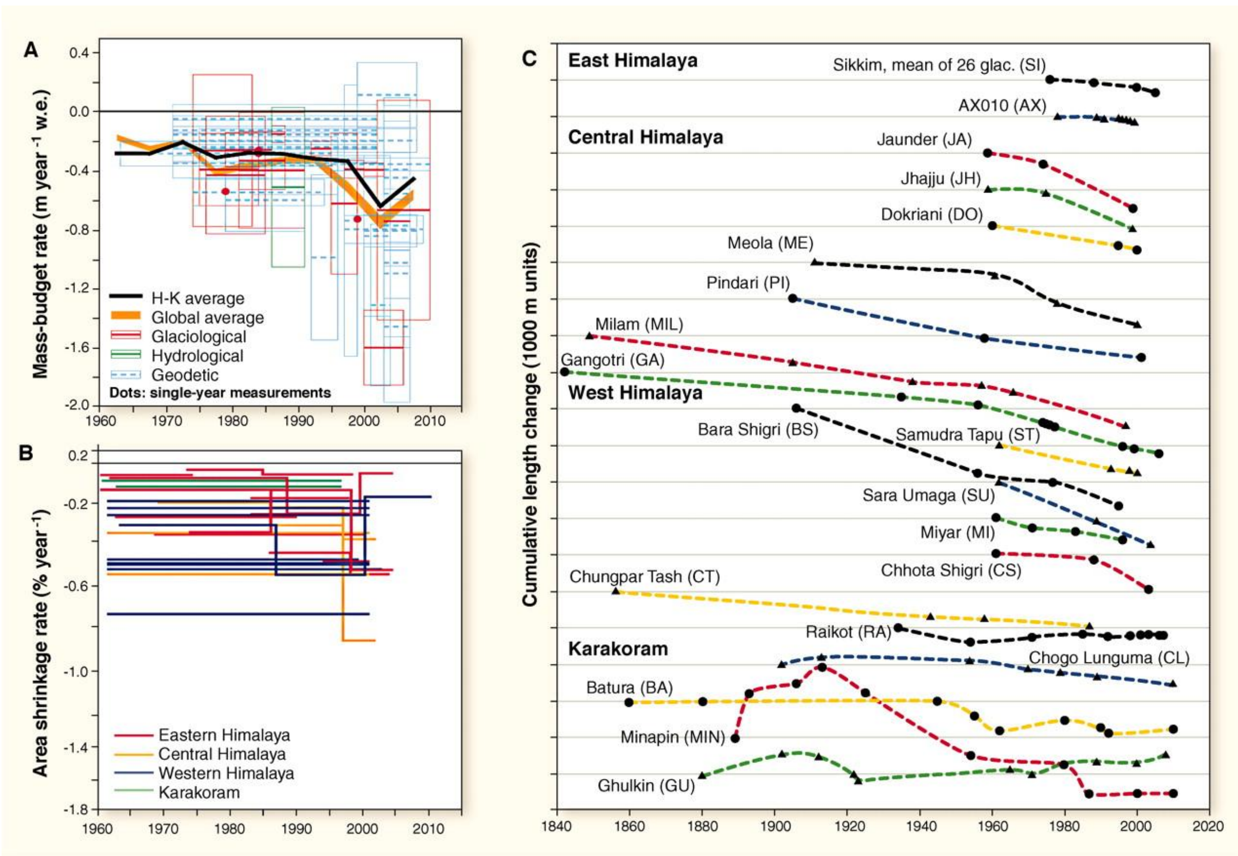

Fig. 1.1- Measured rates of changes reported in the Himalayan glaciers (a) mass balance, (b) Area change (c) Length change. Source: (Bolch et al.,2012)

Hindu-Kush-Himalaya (Himalaya, Karakoram and Hind Kush) abbreviated as HKH, is the largest mountain range of the world. This region is probably one of the critical regions of the world with respect to potential socio-economic impacts of glacier shrinkage (Archer et al., 2010). These glaciers also play an essential role in hydropower generation, agriculture and in maintaining the ecosystem of the region (Moors et al., 2011). Another important reason to study glaciers is that they are one of the best proxies to understand climate change (Anthwal et al., 2006; Kääb et al., 2012). They behave according to the changing climatic conditions around them. Different glaciers behave differently in response to climate change. It has been reported that the Himalayan glaciers are retreating with a faster rate as compared to other glaciers of the world (Close, 2007). Karakoram anomaly has also been reported which shows an advancement in the glacier (Hewitt, 2005). Therefore, in order to understand these patterns in the glacier dynamics, regular monitoring of glaciers is of utmost importance. Several model based studies suggest alarming findings about the Himalayan glaciers (Kulkarni et al., 2013).

In the western Himalayas, about twenty glaciers have been studied including in situ findings, but that is not sufficient for obtaining an understanding about the dynamics of the glaciers of the western Himalayas. Glaciers studied include Chhota Shigri, Bara Shigri, Samudra Tapu, Sara Umaga, Miyar glacier and the Gangotri glacier. All these show shrinkage in their area, mass balance and the length of the glacier (Bolch et al., 2012). A regular monitoring of Chhota Shigri, one of the benchmark glaciers in this region shows a retreat in the length of the glacier (Wagnon et al., 2007; Azam et al., 2012; Ramanathan, 2011). A retreat has also been reported in the Miyar glacier (Kulkarni and Rathore, 2005). Change in the glacier area has also been reported in Chenab, Parbati and Bapsa basin between 1962 and 2004 of the order of 21, 22 and 19 % respectively (Kulkarni et al., 1962). Various studies have been conducted to ascertain the mass balance of glaciers in western Himalayas, and they reported the thinning of the glacier (Berthier et al., 2007; Wagnon et al., 2007). However, some cases have also been reported where glaciers were found to be in steady state (Bahuguna et al., 2014).

There is an ongoing debate about the health of glaciers in this region. While some studies suggest that the glaciers are retreating with an alarming rate, others conclude that either they are stable or retreating with a very nominal rate (Bahuguna et al., 2014). This is due to the unavailability of a comprehensive dataset; deterring conclusive evidence about glacier condition of the Himalayan region. This in turn, necessitates a long term continuous monitoring of the Himalayan glacier which is very important for better understanding its dynamic behavior and Global Climate Observation System (GCOS) (Haeberli et al., 2000).

This data unavailability is mainly due to tough climatic conditions, undulating topography and political hindrances (Bloch et al., 2012). In Himalayas, in-situ data are very limited. Due to logistic limitations, it is not possible to install Automatic Weather Stations (AWS) in all the Himalayan glaciers. So, remote sensing satellite data has emerged as an important tool to study glaciers. Various kinds of datasets such as Landsat, ASTER, SPOT data, LISS data and DEMs (Digital Elevation Models) among others, can be used in glacier studies (Kääb, 2002). Several energy balance algorithms have also been developed with the help of remote sensing in order to understand the land surface temperatures (Bastiaanssen et al., 1998).

Inventory of glaciers is very important as it helps in understanding the climate variability. It is indispensable in terms of estimating the fresh water reserve storage in the form of ice in the glaciers, snout monitoring, area change and finally, mapping. After the Randolph Glacier Inventory 4.0, which provides complete data sets of the shapes of glacier (Pfeffer et al., 2014) it is easier to understand the area and volume changes of the glaciers. As glaciers change their shape, size and area with respect to time, it is imperative to update these datasets on regular time intervals.

With respect to Indian Himalayas, an inventory of glaciers has been made (Sangewar et al., 2009). Space Application center, Ahmedabad, India has also released a glacier inventory in 2010. Although, almost all the glaciers of the Indian Himalayas have been listed, only a few of them have been studied till now. Hence, there is a need to get a better insight into their dynamics using remote sensing, field validation and monitoring of the glaciers.

This study has been initiated in order to achieve the above goal. Very limited literature is available for the Mulkila glacier. As of now, no detailed study has been done which focuses on the temporal variations in the Mulkila glacier. This study is a preliminary attempt to enhance the baseline data set which will enable a better understanding of the glacier's health and its present status, which in turn, will be helpful in obtaining an overall status of western Himalayan glacier behavior and changes. An attempt has also been made to compare the changes in the last few decades in the Mulkila glacier to other well studied glaciers of the region.

In this study, the main focus is on the geospatial study and field validation along with photographs has been done to enhance the present understanding. This dissertation is an attempt to monitor the snout, area volume, mass balance and the geomorphology etc., of the Mulkila glacier. An estimation of the thickness change with the help of DEM has also been attempted.

The present study was carried out keeping in mind the following objectives:

1. To calculate the temporal changes in the length, area, volume and snout fluctuation of Mulkila glacier situated in Himachal Pradesh, Western Himalaya, India
2. To estimate the mass balance of Mulkila glacier using different AAR methods and determine the suitability of DEMs in Indian Himalayas by estimating the elevation change and associated errors.
3. To understand the geomorphology of the Mulkila glacier basin with the help of field photographs.

Chapter 2

LITERATURE

2. Literature Review

2.1 Glaciers in the Indian Himalayan region

Glaciers are defined as masses of slow moving ice, formed by accumulation of snow which later convert into ice due to compaction. They are characteristic features of high altitude regions. Geological Survey of India (GSI) has published an inventory (Sangewar et al., 2009) in which 9575 glaciers were identified in the Indian Himalayan region covering the states of Jammu and Kashmir, Himachal Pradesh, Uttrakhand, Sikkim and Arunachal Pradesh. The total glaciated area was estimated to be around 37,466 km^2 (Raina and Srivastava, 2008).

2.2 Significance of glacier studies

In India, it is very important to study glaciers because a huge population is dependent on the rivers originating from these glaciers. Himalayan glaciers, also known as Asia's water tower (Immerzeel et al., 2010) have also attracted the attention of the world's scientific community as evident from the IPCC fourth assessment report (Solomon, 2007). Despite various studies conducted in the Indian Himalayas, a proper understanding about the glacier health, its dynamics and its role in global climate change is still lagging. A study conducted by the Ministry of Environment, Forest and Climate Change (MoEF & CC) in 2009 concluded that even though these glaciers are not retreating with an alarming rate, they have their own response to the changing climatic conditions. It is very clear that anthropogenic activities have affected the climate. Henceforth, various national and international agencies, both governmental and non-governmental, are working on Indian Himalayas to understand the effects and dynamics with changing climatic conditions caused by both anthropogenic activity as well as natural reasons.

Himalayan glacier study is also important because it is a huge reservoir of freshwater in the form of ice outside polar regions and its hydrological importance cannot be overlooked (Krishna, 1996; Viviroli and Daniel, 2003; Messerli, 2003; Messerli and Viviroli; 2004; Weingartner, 2004). Discharge water of these glaciers are used in various sectors viz. agriculture, consumption, hydroelectricity and other domestic uses.

Different glaciers all around the world are behaving differently depending upon the micro-climatic conditions. Some glaciers are retreating at a faster rate as compared to others (Paul et al., 2004; Barry, 2006; Ren et al., 2006; Zemp et al., 2006). This retreating trend was also reported in the glaciers of Indian Himalayas (Bolch et al., 2007; Kadota et al., 2000; Khromova et al., 2006; Ren et al., 2006). According to fourth IPCC report (2007), Himalayan glaciers are retreating at a faster rate than that of other glaciers of the world (Cruz, et al., 2007). It has been found that mass loss of Himalayan glaciers has been reported to be about 5.5 % in last three decades and also that small and valley glaciers have faster retreating rates than other glaciers (Bajracharya et al., 2006). In last three decades, Himalayan glaciers are retreating with increased rate of melting (Barry, 2006; Ren et al., 2006). It indicates the changing climatic conditions in last few decades (Hewitt, 2005; Hinkel and Nelson, 2003; Maisch, 2000; Racoviteanu et al., 2008b; Zemp et al., 2006).

Chhota Shigri glacier in Chandra basin in the western Himalayas, is considered as a benchmark glacier of this region indicative of the effect of climate change on glacier dynamics (Azam et al., 2014). This study observed a mass loss between 1969 and 1985 as also from 2001 to 2012. Glacier was in a steady state between time periods from 1986 to 2000. In further studies on Chhota Shigri glacier, the mass balance was reported to be -1.4 mw.e. to +0.1 mw.e (Wagnon et al., 2007). Further studies show a decrease in Accumulation Area Ration (AAR) of the glacier which is itself an indicator of negative mass balance of the glacier (Berthier et al., 2007). A long term study of the Himalayan glaciers, which is considered to be a complex system, is essential for a proper understanding of the health of the glaciers and its role in the present changing global climatic conditions. For such long term monitoring, support systems by various agencies are also needed because it is not possible to study these glaciers without prior involvement of various stakeholders.

2.3 Remote Sensing and Glacier Study

In-situ data for whole of the Himalayan glaciers cannot be obtained because of the large area, inaccessible terrain conditions and political hindrance (Yale et al., 2017). Data are insufficient for glacier health estimation by means of mass balance, hydrology and dynamics in this region. So, satellite data plays a very crucial role as it enables regular and long term monitoring. Remote sensing is an important tool to understand glacier dynamics. Various remote sensing studies were done and a brief idea was obtained regarding these glaciers. For e.g., an attempt to understand the decadal change in glacier in Cordillera Balnca was made (Racoviteanu et al., 2008a), which proved helpful in understanding area change and thinning of the glacier.

Main governing factor in monitoring the glaciers with the help of satellite data is the spectral response of its components. Different objects have different spectral signature which depends on the composition, density and grain size etc. In some studies it has been found that reflection from snow is anisotropic, because of which, there is enhancement of specular scattering due to reflection from ice crystals (Hall et al., 1993). ISOCLUSTER classification which is also known as unsupervised classification is also done to differentiate between different components of the glaciers (Venkateswarlu et al., 1992).

Snow cover monitoring has been possible with the help of various satellite datasets (Immerzeel et al., 2009). Long range monitoring of glacier is possible with the help of remote sensing (Bhambri et al., 2011; Kulkarni et al., 2011). Various datasets provided by different satellites have been a valuable asset in understanding the dynamics of the glacier. Glacier velocity estimation has also been done with the help of ASTER and SRTM data set for Himalayas (Kaab, 2005). Maximum velocity was reported as 100-200m year $^{-1}$ in Bhutan Himalayas. Another property of glaciers, the mass balance, can be estimated with the help of remote sensing. Snout monitoring of glacier is also possible with the help of satellite data. Frontal recession was observed of Gangotri glacier between 1965 andS 2006 with the help of remote sensing and satellite data (Bhambri et al., 2012). Retreat of Gangotri glacier using PAN stereo data of 2000-2001 has also been reported (Bahuguna et al., 2007). Glacier retreat of 1868 Himalayan glaciers in 11 basins has been reported between 1962 and 2001/2 and area change from 6,332 to 5,369 km observed (Kulkarni et al., 2011). Such long term study is possible with help of satellite data and remote sensing. Recent advancement in remote sensing techniques and satellite data resolution is going on, critical revolution has taken place in glacier monitoring which has been very beneficial to study the changes occurring in glacier behavior.

Estimation of volume of the glacier is also very important in order to obtain information about the fresh water reserve. Various empirical relations have been developed (Frey et al., 2014), and applied to various Alpine glaciers. All these equations are glacier area dependent. With respect to the Indian Himalayas, a specific relation has been developed (Chaohai and Sharma; 1998).

$$H = -11.32 + 53.21F^{0.3}$$

H denotes the mean depth (m) of the glacier and F is total glacier area (km^2).

Although there is no proper validation of different equations developed, these methods are helpful in obtaining a brief idea about the glacier volume change with time.

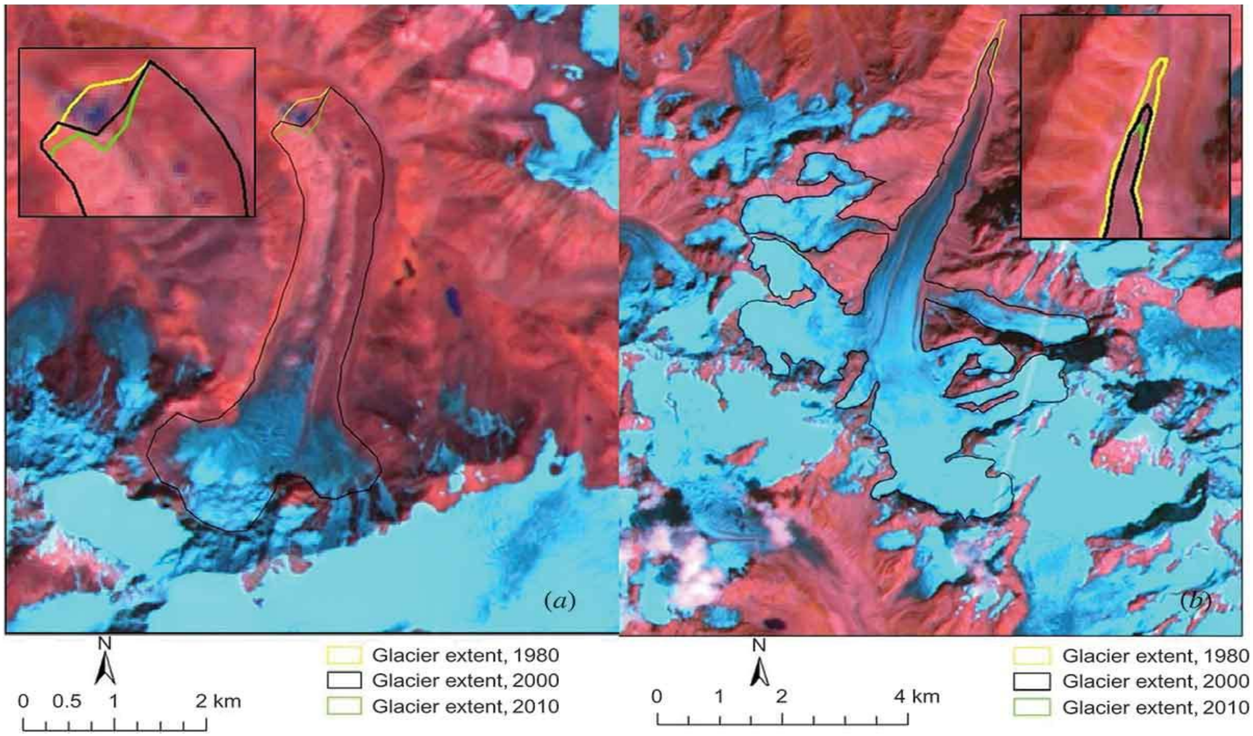

Fig. 2.1- Monitoring the glacier extent in 1980, 2000 and 2010 with the help of remote sensing using LISS image for (a) Hamtah (b) Chhota Shigri glacier. Source: (Pandey and Venkataraman, 2013).

Various techniques and equations such as AAR related mass balance of the glacier have been developed using results obtained from remote sensing. It is one of the most important and sensitive features for the estimation of the mass balance of the glacier. Various statistical equations have been evolved to estimate annual glacier wide mass balance (Kulkarni et al., 2004; Mandal et al., 2016; Pratap et al., 2015; Tawde et al., 2016). Initially (Kulkarni, 1992) developed the equation with the help of AAR and annual glacier mass balance (R^2=0.80) in two glaciers in Himachal Pradesh named as Shaune Garang and Gor Garang glacier in the Bapsa Basin. The monitoring of these two glaciers was done by Geological Survey of India. This gives a brief idea about the health of the glacier. As these equations give different result for the same AAR, it cannot be considered as final result of the mass balance, but it can be considered as indicator of glacier health.

Digital Elevation Models (DEM) differencing is another important tool for understanding the glacier behavior. Glacier thickness change can be calculated with the help of DEM differencing.

In western Himalayas (Berthier et al., 2007; Vincent et al., 2013; Vijay and Braun, 2016) in Pamir Karakoram Himalaya (Gardelle et al., 2013) DEM differencing was used to estimate mass balance of the glacier. In Karakoram glaciers in early twenty- first century, slight mass gain was reported with the help of DEM differencing (Gardelle et al., 2012). Proper data correction is needed to get better result. Different DEM corrections have been mentioned in which various bias corrections are carried out to minimize the error (Nuth and Kääb, 2011). Shuttle Radar Topographic Mission (SRTM) data whose acquisition date is Feb, 2000 has a demerit associated with it. The C band and X bands of the SRTM have a penetration effect, which decreases the accuracy of the result. An assessment of SRTM performance has also been done (Rodríguez et al., 2006). For non-glaciated terrains, elevation dependent corrections have also been suggested for the SRTM (Berthier et al., 2006). These corrections have been applied to various studies and some better results were obtained (Schiefer et al., 2007; Surazakov and Aizen, 2006) although these bias may be because of the varying resolutions (Paul, 2008). The depth of penetration was estimated up to 10 meters for the snow and ice (Rignot and Echelmeyer, 2001).This depth may vary for different objects, so there would certainly be some error associated with DEM differencing if SRTM data is taken into consideration. Various other properties of the glaciers can be monitored with the help of remote sensing. Regular monitoring of the area change of the glacier with respect to time is important to understand the dynamic behavior of the glacier.

2.4 Geomorphology of the Glaciers

Various kinds of landforms are formed by glaciers. Glacier geomoprhology is an important field in glaciology. Glacier movement provides a platform for the glacial landform. Study of the glacier geomoprhology, landforms and their relation to changing climate are important (Napieralski et al., 2007). According to Boulton, (1982), field study of glacial erosion is centered around three themes (i) identification of the small feature processes such as abrasion, stoss and lee topography (ii) descriptions of medium scale erosional features such as cirques and U-shaped valleys and (iii) identification of patterns of erosion on a large scale. Mainly three basic activities take part in all kind of landform formation in any geological formation with different agents that is erosion, transportation and deposition (Ritter et al., 1995). Different kinds of physical and chemical weathering are carried out by different agents. In case of glacial landforms, phyical weathering is the causative factor. Various kinds of unconsolidated, weathered and solidified landform formations take place in glaciers. Extensive study has been done on the sediment (Brodzikowski and van Loon, 1991; Benn and Evans, 1998) but in case of landform of the glacier there is scarcity of the data even though they are good indicator of the paleoclimatic conditions (Close, 1867). So there should be some more focus on the glacier geomorphology because they have high potential to provide various information of the glacier.

In the last few decades there has been advancement in the study of the glacier geomorphology. Various techniques such as Optically-Stimulated Luminescence (OSL) dating have been used to study the dating of glacial landform such as moraines (Owen et al., 2001). Various other remote sensing techniques has evolved with time to study the glacier such as aerial photography (Prest et al., 1968), satellite images (Punkari, 1982) and digital elevation models (Clark and Meehan, 2001) have been used. Specially focusing on the glacier landforms, it can be inferred that most of the landforms formed are indicators of the changing climatic conditions. Glacier sediments formed due to erosion are least sorted because of least transportation of the sediments (Tulaczyk et al., 1998). Mostly sediments are angular and larger in size (Shilts, 1993).

Various important landform are formed by the glaciers. Cirque, Horn, Arete, Snout, Tallus Cone, Crevasses, Ice facies, U shaped valley, Hanging valley, different kinds of Moraines and many more are important landforms. They have a lot of information about the glacier regarding its paleoclimate. Main source of the debris of the glacier is debris flow, rock falls, rock avalanche and snow avalanches (Benn et al., 2003).

2.5 Glacier related Hazards

Climate change acts as stimulating agent for various glacier hazards. It may cause huge destruction, death, injury and harm to natural resources. So it is important to have an eye on these glacier related hazards. Cryospheric hazards should be considered from physical hazards point as well as human response (Whiteman, 2011). It is very important to monitor the Glacier Lake and permafrost regularly (Kääb et al., 2003).

<u>Glacier lake Outburst Floods (GLOF):</u>

Glacier melt water sometimes form a lake because flow is restricted or blocked by moraines or debris. Various studies have been conducted on the formation of the glacial lake in Himalayas which infer the formation of lake in Himalayas (Ives et al., 2010). Regular melting adds water to these lake, after certain time lake water overflows crossing the obstacle and causes a flood which is very hazardous. Uttrakhand Kedarnath tragedy, 2013 in which a huge loss occurred was due to GLOF (Das et al., 2015; Pati Ray et al., 2016) It happens when loose sediment which form the wall of the lake is unable to hold the further melt and overburden of the water breaks the wall which causes flood. Climate change has huge impact on the GLOF (Bajracharya and Mool, 2010). It is important to monitor the high altitude lakes to prevent such tragedies again.

Flash Floods:

These are also glacial hazards. In Himalayan region flash floods occur rapidly with little time for warning. It contains huge and rapidly flowing water with sediment and debris flowing with high velocity. For the flash flood rain fall is a triggering agent. It comes suddenly and lasts for several minutes to several days. Cloudburst, accumulation of monsoon clouds because to topographic barriers are main causes of the flash flood. It occurred in Ladakh in 2010, main reason behind it was cloudburst in the area.

2.6 Mulkila Glacier:

This glacier is located in Lahual and Spiti valley, Himachal Pradesh. According to GSI 2009, this is one of the largest glacier in the region. Mulkila glacier is debris cover glacier, rate of melting is slower than clear glacier (Powell, D., 2012), but no proper in situ data is available regarding mass balance of the glacier. Mulkila is one of the important glaciers of the Bhaga basin including Milang and Gangstang as these are the glaciers with largest area in the basin (Birajdar et al., 2014).

After the inventory published by GSI there is no major particular study conducted on this glacier. There is a lack of literature on the Mulkila glacier. A literature which provides information about the Mulkila is regarding its firn line altitude (Guo et al., 2014). Firn line may be defined as the altitude at which snow remains throughout the year (Seidel et al., 1997). Firn line altitude is helpful in many ways; one of the important advantages is predation of the future change in snow cover of the glacier (Kaur et al., 2009). Microclimatic conditions influence the firn line (Kerr and Sugden, 1994) so its fluctuation is an indicator of climatic change.

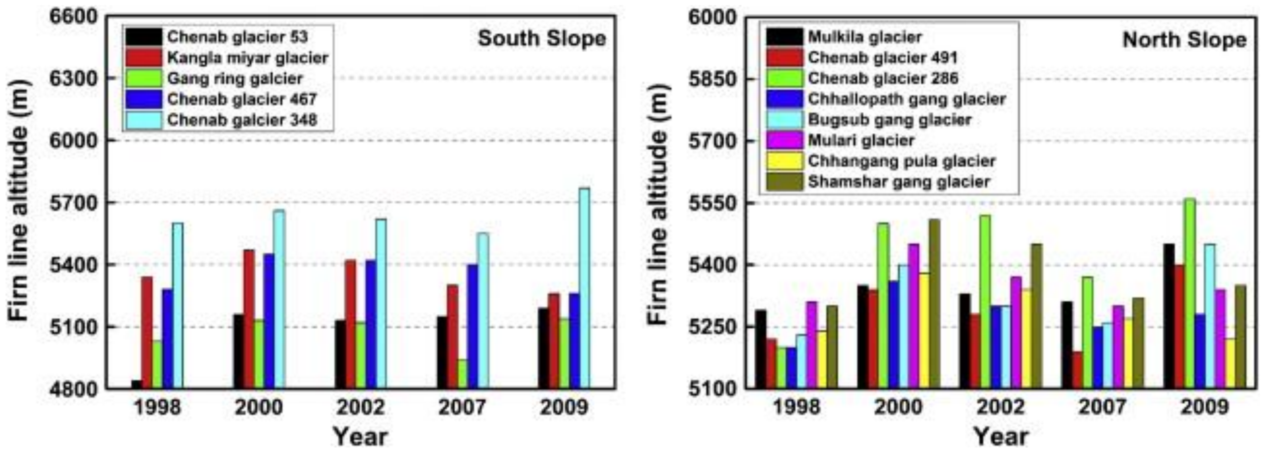

Fig. 2.2. Selected glaciers on the southern slope and northern slope and their firn line altitudes in 1998, 2000, 2002, 2007 and 2009 (Guo et al., 2014)

In few literature in which snow cover and climate variability of Bhaga Basin is studied they have included Mulkila in their study (Shehmani et al., 2015). Ray and Sreedhar, (2011) did altitudinal profiling of the glacier in North Western Himalayas, they included Mulkila glacier in their study and reported that the peak of the glacier is around 6417m. A retreat rate of 17.47 m year $^{-1}$ of Mulkila glacier was reported (Pandey and Venkataraman, 2013). Thinning of Mulkila was reported up to -50m while observing the whole northern Himalayas (Vincent et al., 2013), other studies also reported the thinning of the Mulkila glacier (Vijay and Braun, 2016).

There is unavailability of proper datasets and literature on the Mulkila glacier, so this study will contribute in primary investigation, understanding Mulkila glacier behavior and its dynamics with the changing climatic scenario. In this study an attempt is made to monitor snout, area, volume of the glacier. To monitor the health of the glacier, mass balance is also estimated with help of AAR methods and glacier thinning is also estimated with the help of DEM differentiation. For validation of the study various field photographs have been taken and effort is made to trace the various geomorphic features and landforms of the valley of Mulkila glacier.

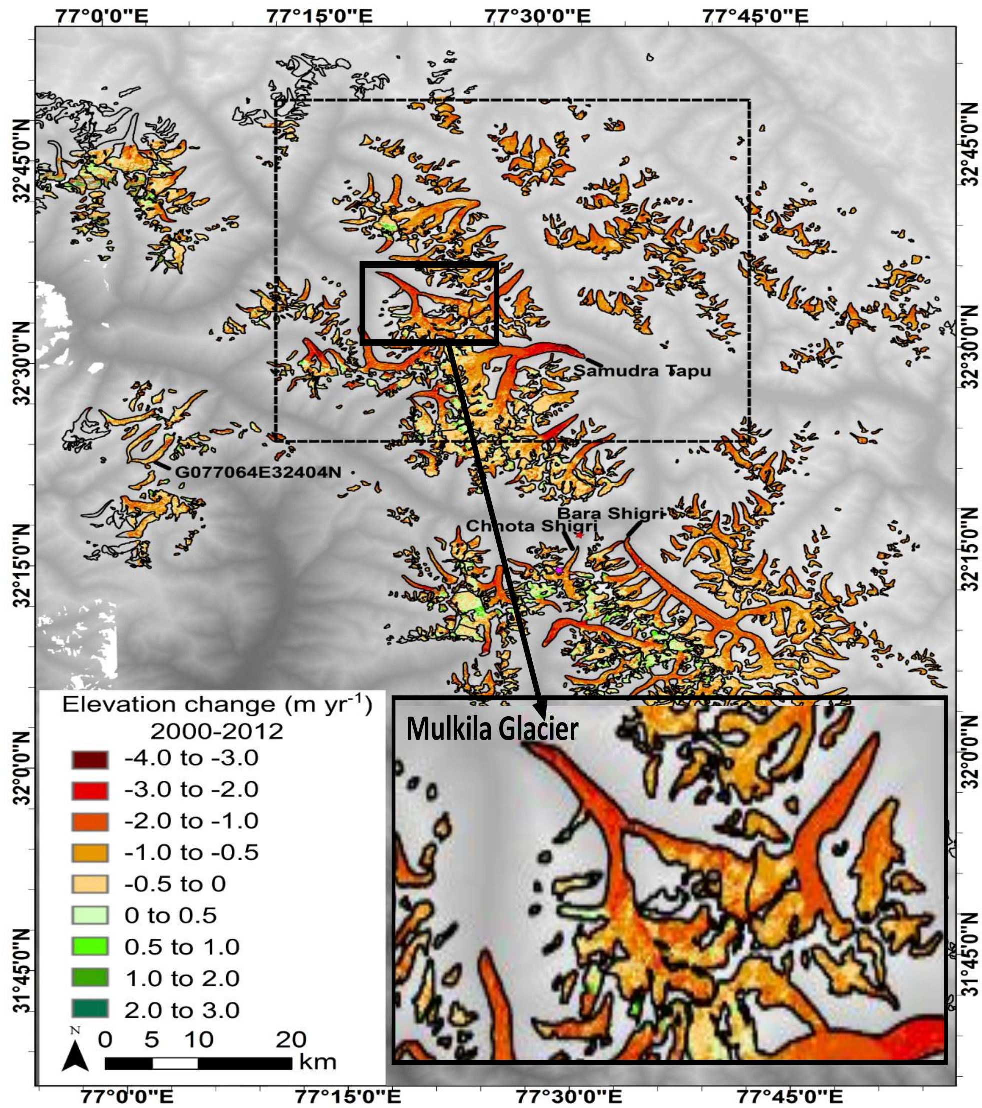

Fig. 2.3- Map of the elevation change of the glacier in Lahual Spiti region between February 2000 and October 2011. In the inset mean, and standard deviation on/off the glacier. Image source: (Vijay and Braun, 2016)

Chapter 3

STUDY AREA

3. STUDY AREA-

This study is conducted on Mulkila glacier (GSI ID no IN 5Q21211 170) which comes in Bhaga river basin (Sangewar et al., 2009). The entire study area lies in Lahual Spiti district of the Himachal Pradesh. The map of the study area (Figure 3.1) indicates the nearest bench mark glacier of western Himalaya that is Chhota Shigri (Azam et al., 2012). Another one of the largest glacier of the western Himalaya that is Samudra Tapu is also located in the map (Figure 3.1). Nearest town is all these glacier is Manali which is also shown in the map.

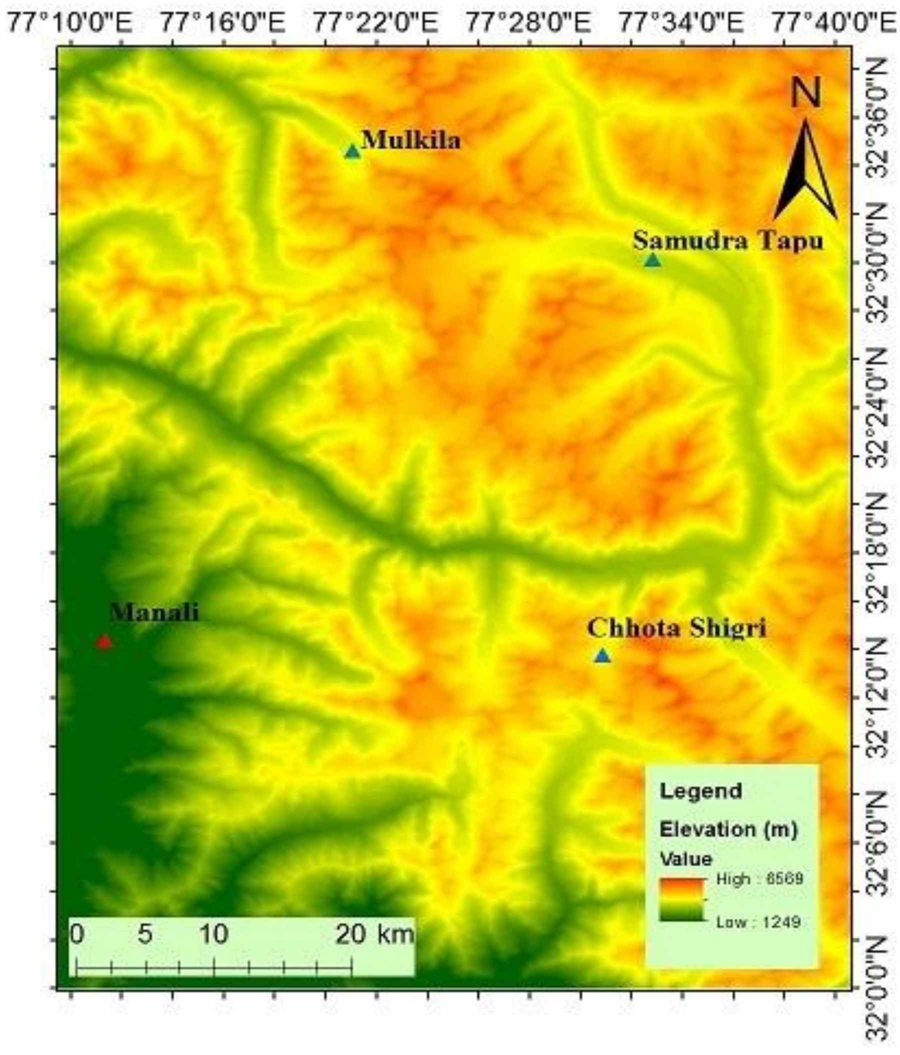

Figure 3.1- Location map of Mulkila glacier. Nearest well known glacier to Mulkila are Ssamudra Tapu and Chhota Shigri glacier. Manali nearest town to the glacier. Map prepared with help of ASTER GDEM, showing the elevation range of the galcier.

Mulkila glacier in the Bhaga basin, the nearest village to the glacier is Darcha. It is one of the large glacier in the Himachal Pradesh. Length of the glacier is 13.50km, accumulation and ablation area has their orientation in westward and northwestward respectively (Figure 3.2).

Mulkila glacier is having a tributary which also 14.60 km long. There is a cliff which bifurcate the glacier in two branches. Overall general information about the glacier is mentioned in the Table 3.1 which has all the general information about the glacier.

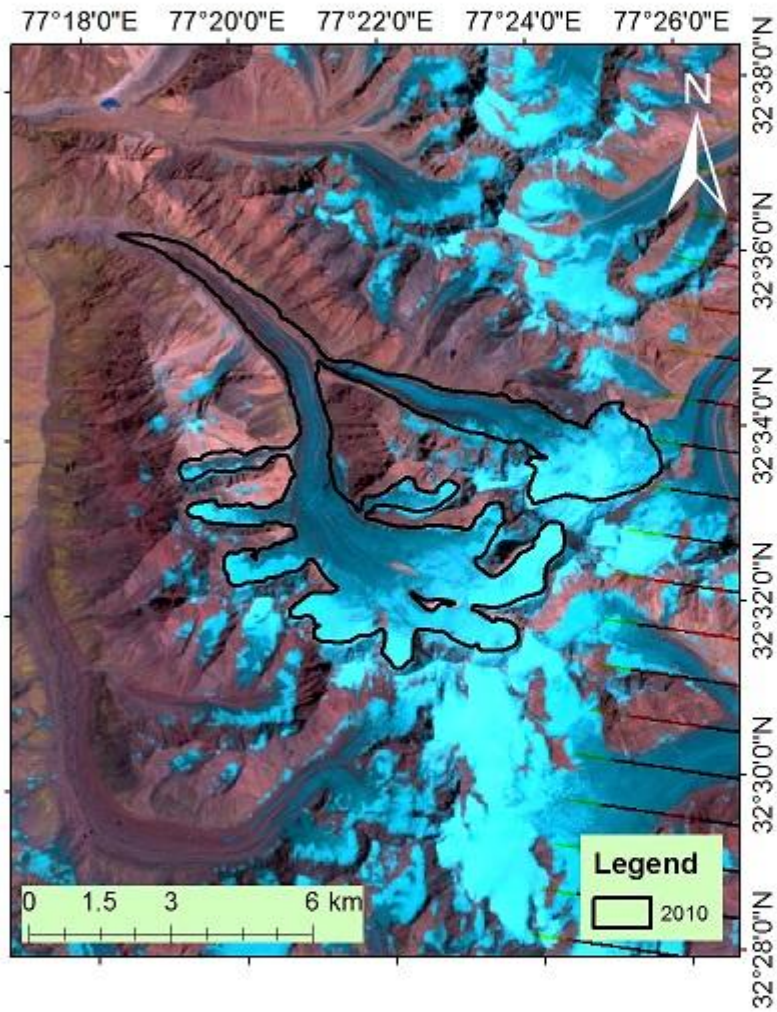

Figure 3.2- Map of Mulkila glacier of 2010, prepared with the FCC of band combination 5, 4 and 3. Orientation direction of the accumulation and ablation is toward west and north west.

Table 3.1- Geographical and topographical information of the Mulkila glacier. The data obtained by GSI Himalayan glacier inventory 2009.

General features	
Country, State	India, Himachal Pradesh
Mountain Range	Western Himalaya
District	Lahaul and Spiti
Drainage System	Bhaga River- Indus River (Chenab Branch)
Climate Zone	Monsoon – arid transition

Glacier Characteristics	
Latitude	$32^{0}33^{'}17^{''}$
Longitude	$77^{0}21^{'}24^{''}$
Maximum elevation	6040m
Minimum Elevation	4075m
Snout Position	N$32^{0}16^{'}18^{''}$; E $77^{0}18^{'}47^{''}$
Mulkila glacier area	28.63 km^2
Accumulation	21.05 km^2
Ablation	7.58 km^2
Glacier length	14.60 km
Accumulation	7.70km
Ablation	6.90km
Mean width	4.30 km
Volume	2.863 km^3
Orientation	
Accumulation	West
Ablation	North west

As the climatic condition of the area is concerned, as the western Himalaya receives precipitation of two types in a year, one during summers i.e. July to September through Indian summer monsoon and second one is in January to April due to westerlies (Bookhagen and Burbank, 2006), so it can be said the Mulkila glacier comes under monsoon arid transition zone where both types of circulation contributes to annual precipitation. So we can say that the health of the glacier is dependent on the amount of the precipitation received by both of these precipitation system.

Mulkila glacier is highly debris covered glacier. The reason behind the high debris is its valley walls which are very steep and unstable. Rock falls and avalanches are very common in the valley, even minor rain fall can cause the rock fall. Glacier valley is very narrow in comparison to Chhota Shigri glacier.

Chapter 4

DATASET AND METHODOLOGY

4.1 Dataset Used in the Study-

Landsat image is used in the study from 1980 to 2015 to see a gradual change in the glaciers which were available on the United State Geological Survey (USGS) website for glacier mapping. During the data selection to be used for the study two things were taken under consideration, one is cloud cover not more than 20% and second one is image should be the representative of the end of ablation season August to October, because the snow cover will be minimum so that actual shape of the glacier will be visible (Andreassen et al., 2008; Paul et al., 2013). Image selected is from 1980 after that 1989 then from 2000 to 2015 each year.

Table 4.1- Data set used with the specification of their sensor and path, row of the satellite and band combination to make FCC from 1980 to 2015.

Satellite/ Sensor	Year	Path/Row	Band Combination
Landsat 3/MSS	1980	158/37	1,2,3
Landsat 5/TM	1989	147/37	5,4,3
Landsat 7/TM	2000	147/37	5,4,3
Landsat 7/TM	2001	147/37	5,4,3
Landsat 7/TM	2002	147/37	5,4,3
Landsat 7/TM	2003	147/37	5,4,3
Landsat 7/TM	2004	147/37	5,4,3
Landsat 7/TM	2005	147/37	5,4,3
Landsat 7/TM	2006	147/37	5,4,3
Landsat 7/TM	2007	147/37	5,4,3
Landsat 7/TM	2008	147/37	5,4,3
Landsat 7/TM	2009	147/37	5,4,3
Landsat 7/TM	2010	147/37	5,4,3
Landsat 7/TM	2011	147/37	5,4,3
Landsat 7/TM	2012	147/37	5,4,3
Landsat 7/TM	2013	147/37	5,4,3
Landsat 7/TM	2014	147/37	5,4,3
Landsat 7/TM	2015	147/37	5,4,3

False color composite (FCC) of all year image was made and then pan sharpening (King and Wang 2001; Shah et al., 2008) was done to increase the resolution of the FCC (Jansson and Glasser, 2005) (Figure 4.1). After this the mapping of the glacier was done in ArcGis software to digitize all the image manually Bhambri et al., 2009 reported that band ration and the NDSI are not suitable methods to delineate the Himalayan glacier because they are mostly debris covered so manual digitization is best method.

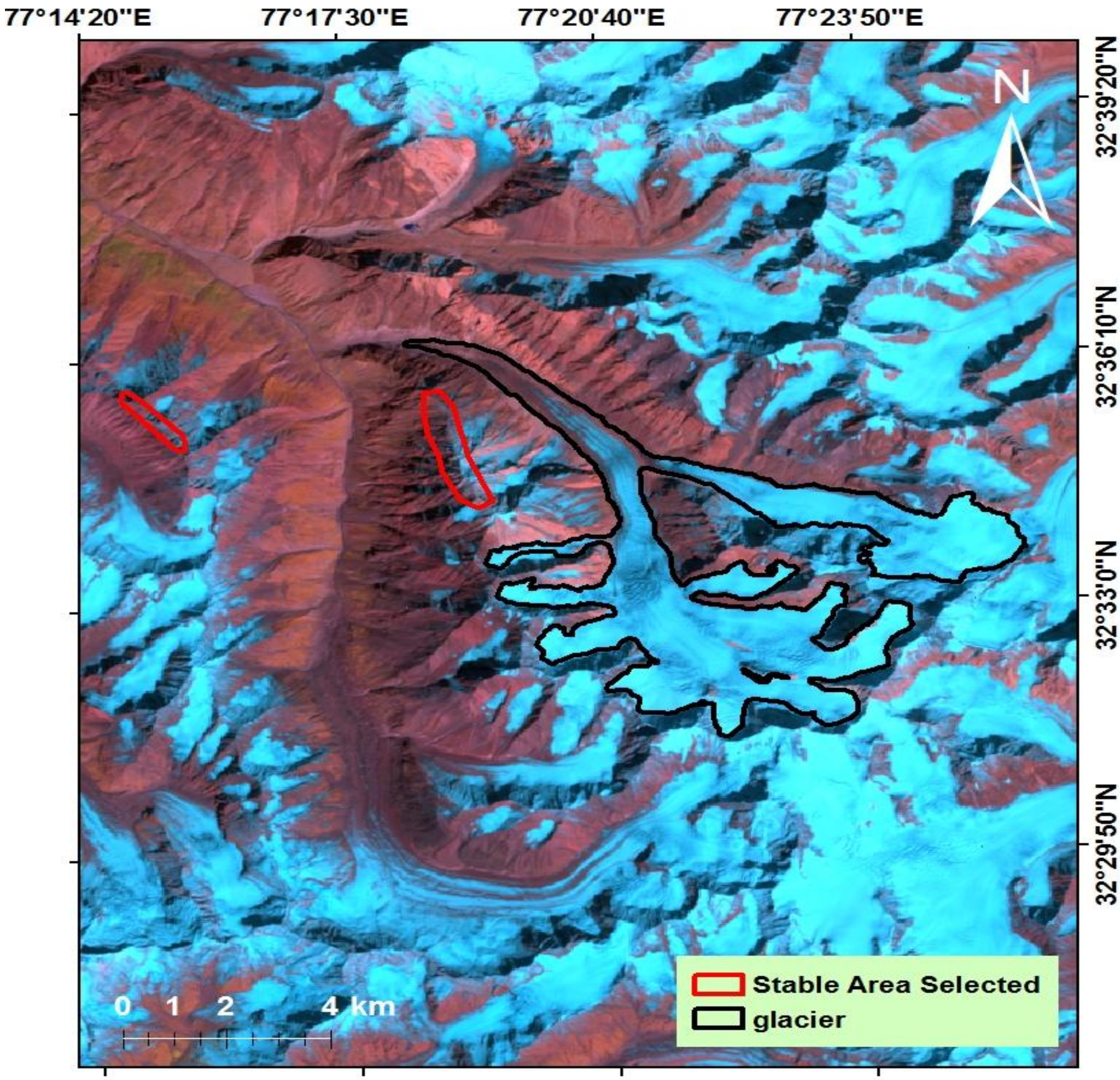

Figure 4.1 – FCC of the whole glacier region and showing Mulkila Glacier with black Boundary. The stable areas chosen to estimate the error associated with DEM are highlighted. Mainly peaks are chosen as stable area in the region

4.2 Area and AAR estimation -

Area calculation done with the help to shape files made manually with the digitization. Attribute table of the each shape provided area for each year in square kilometers. In case to find the change in accumulation and ablation area composite of bands was also made (Aniya et al., 1996) to estimate the differentiation between snow, ice and debris, this technique has been used to study the different glaciers. This method helped in obtaining the value of AAR, which was further used for mass balance study. A snow line was drawn manually which divide glacier in accumulation and ablation area. Above this line there is snow only.

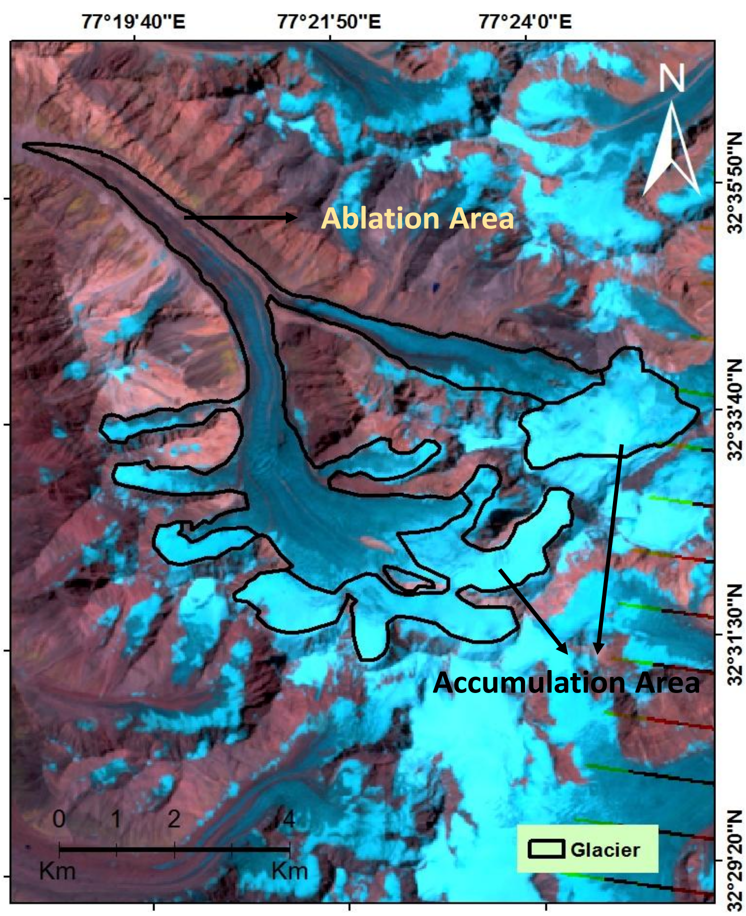

Figure 4.2- Differentiation between Snow and Ice and Snow Line with help of Landsat 7 imagery, ablation and accumulation area of the glacier. FCC if of the year 2004.

4.3 Volume Estimation equations-

In this study volume estimation of the glacier is also performed so that estimation of fresh water reserve can be done. There are various methods to estimate the ice reserve has been attempted with the help of different equations developed as described below. These methods are based mainly on the area- related volume thickness.

Method 1 and 2- Bahr, 1997 and Chen and Ohmura, 1990 used as by Frey et al., 2014 to estimate the volume of the glacier in Himalayan and Karakoram region.

$$h = cA^{\gamma - 1}$$

$$V = cA^{\gamma}$$

Parameters applied in relation

Source	c	γ
Chen and Ohmura(1990)	0.2055	1.360
Bahr et al. (1997)	0.191	1.375

Method 3 is based on the relation established by Bruckl, (1970), this was used in the Swiss glacier by Muller et al., 1976

$$h = 5.2 + 15.4 \times A^{0.5}$$

$$V = h \times A$$

Method 4 is based on the Chaohai and Sharma 1998 to estimate the volume of the Himalayan glacier; they used the empirical relation as below

$$h = -11.32 + 53.21 \times A^{0.3}$$

$$V = h \times A$$

In the above two relations h is the mean thickness, the V is the volume of ice reserved in glacier and A is the area of the glacier.

With the help of all these equations volume of the glacier was estimated and a comparison between all these methods result was done. For having a better comparison the mean of the all the results obtained by different methods was calculated.

4.4 Mass balance estimation and DEM differentiation-

There are various methods to estimate the mass balance of the glaciers, but in this study mainly AAR based methods have been applied.

As mentioned in previous chapter there are various equations have been developed which estimate the annual mass balance of glaciers. AAR and Equilibrium Line Altitude are two major properties of the glacier, and useful in estimation of the mass balance (Kulkarni,1992; Benn and Lehmkuhl, 2000) but they changes according to the micro-climatic conditions of the glacier which makes them sensitive to the climate change. In present study mainly four equations developed by Kulkarni et al., 2004 (1); Mandal et al., 2016 (2); Pratap et al., 2015 (3); Tawde et al., 2016 (4) are used. These equations have been developed with the help of in situ data available of the different Himalayan glaciers.

Equations are as fallows-

$$Y= (2.4301*X) - 1.20187 \qquad (1)$$

$$Y = (0.037*X \%) – 2.336 \qquad (2)$$

$$Y= (1.9433*X) – 1.3149 \qquad (3)$$

$$Y= (1.74*X) - 1.232 \qquad (4)$$

Y is annual specific mass balance (m w.e.) and X is AAR.

In DEM differencing two different time period DEMs were selected which are freely available. SRTM is of Feb 2010, ASTER GDEM data is of October 2011.

First problem in using these DEMs are that they are of different months especially in case of SRTM which is of the month of February, this is the time when glacier is covered with snow and the prediction of actual elevation of the glacier is problematic but in the case of ASTER GDEM best thing is that its acquisition date is in month of October 2011. It is the end of the ablation season which makes it suitable for glacier study.

Second is the penetration of the C band of SRTM, it penetrates in the snow and ice, so actual elevation does not come from this. Rignot and Echelmeyer, 2001 suggested that the penetration of the C band of the SRTM is up to 10m. Various other studies has been done to minimize the error relate to SRTM error (Frey and Paul, 2012; Nuth and Kääb, 2011).

For Better result change in elevation of some stable areas were calculated, these area were chosen with the help of FCC made which would have minimum or no elevation change with this expand of time (Figure 4.1), so this elevation change can be considered as the error of the DEM. This error is associated with the elevation change of the glacier.

Separate AOI was made for the glacier, elevation change is estimated for both of them, so that a brief idea could be made regarding thickness change of the glacier.

All these data processing is done with the help of Erdas Imagine 2014 and ArcGis 10.2.

4.5 Geomorphology study-

In the geomorphological study various landforms were tried to identify. For identifying maximum landform and features associated with these landform help of Google Earth was also taken. Moraines length and elevation, elevation of the horns were estimated with the help of Google Earth. Field study was also conducted to understand the geomorphology was done. Different landforms and glacier features were seen and photographs also taken. These field photographs are also useful to validate the study.

Chapter 5

Results and Discussion

5.1 Snout Retreat

The snout retreat indicates the health of the glacier. A regular year wise monitoring of snout position of Mulkila glacier has been done using a series of Landsat data. The glacier snout has been receded over the study period between 1980 and 2015. Table 2 represents retreat rate per year as well as decadal retreat.

Table 5.1- Snout retreat from 1980 to 2015 of Mulkila glacier. The retreat was monitored by the FCC made using band 1,2 and 3 and 5,4 and 3 for Landsat 5 and 7 respectively.

Time Period	Retreat (m)
1980-1989	214.52
1989-2000	92.32
2000-2001	48.6
2001-2002	52.8
2002-2003	57.7
2003-2004	32.74
2004-2005	34.6
2005-2006	13.9
2006-2007	7.13
2007-2008	15.81
2008-2009	17.53
2009-2010	15.03
2010-2011	15.3
2011-2012	13.44
2012-2013	17.1
2013-2014	9.92
2014-2015	22.34
1980 to 2015	**710.05**

The average retreat is recorded as 19.40 m year^{-1} during the time period of the 1980 to 2015. On comparing the decadel retreat of snout from 1980 to 1989, 1989 to 2000 and 2000 to 2010, maximum retreat is observed between 2000 and 2010 of 295.84 m, from 1989 to 2000 it is 92.32 m and from 1980 to 1989 it is 214.52 m. From above data set it can be infrered that the snout of Mulkila glacier is certainly retreating but with a diffrential rates in different years. During the last 15 years the maximum retreat is from 2002 to 2003 after that per year retreat has been decresed. The change in the position of the snout from 1980 to 2015 is approximetly 710.05 m. The snout retreat of Mulkila glacier has also been reported by the Pandey and Venkatraman.,(2013). They have reported a retreat rate of the 17.47 meters year^{-1} during the time period of 1980 to 2010. In this study retreat rate is reported as 19.47 m $year^{-1}$ which is greater than the retreat reported earlier. This shows that the rate of the retreat has been incresed after 2010, although it may be also taken as the error of the remote sensing study which gives a diffrence in thses two studies.

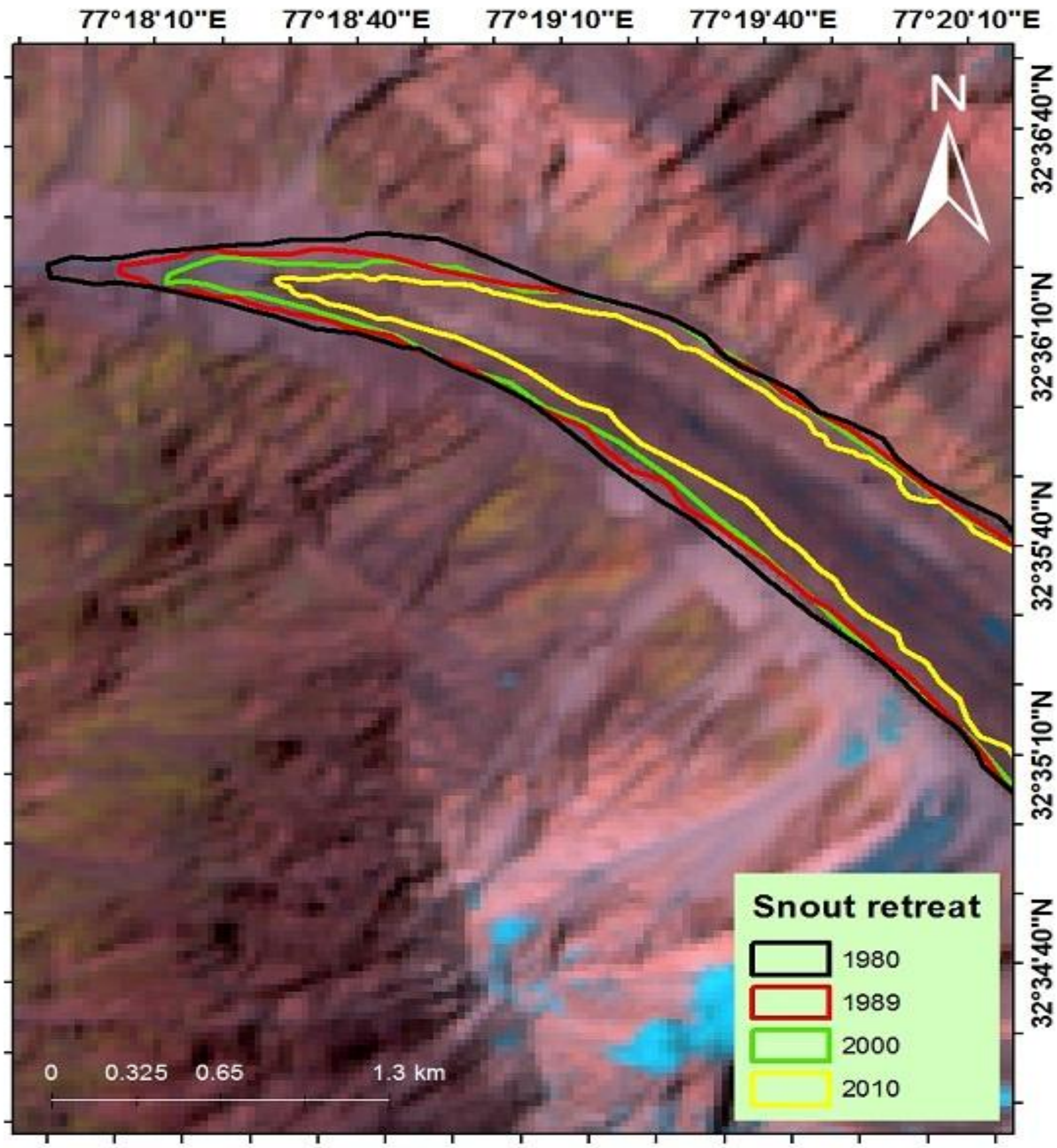

Figure 5.1- Decadal snout retreat of Mulkila glacier between 1980 and 2010. Each year snout are indicated with different colour. FCC on the back ground is of 2000 made with the Landsat 7.

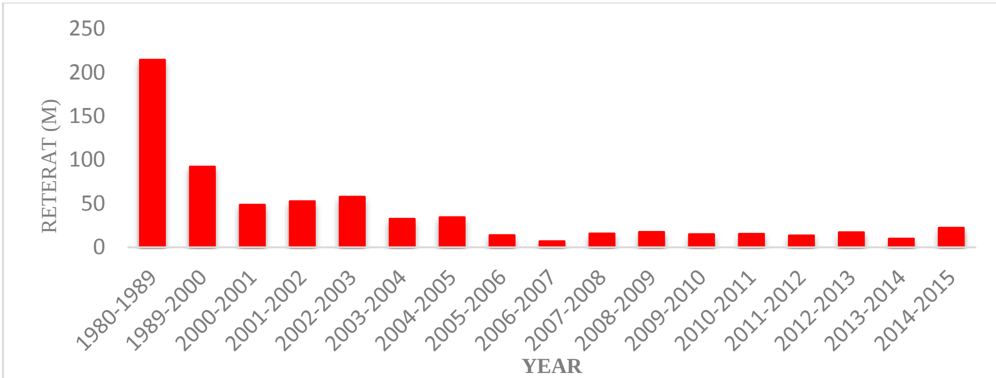

Figure 5.2- Bar plot of rate of retreat of snout of glacier between 1980 and 2015. Results are obtained by regular year wise monitoring of the snout with the help of Landsat satellite data.

The trend observed in the retreat of the snout of the Mulkila glacier shows a enhanced retreat during 2001 to 2005. After that a more or less similar rate of retreat is observed. There are various studies have reported that there is increase in the mean temperature and decrease in the snowfall in western Himalayas suring this time period (Dimri et al., 2013; Shekhar et al., 2010) A comapsrion of snout retreat is done for the different glaciers in the Lahual spiti region (Table 5.2). The study is conducted between 1980 and 2010. Glaciers are retreating with the varying rates which depends on the different factors.

Table 5.2- A comparison of the snout retreat of different glaciers in Lahaul Spiti region. Source (Pandey and Venkataraman, 2013)

S.No.	Glacier	Rate of Retreat $myear^{-1}$(1980 to 2010)
1	Panchi I	17.23
2	Hmatah	16.80
3	Chhota Shigri	7.33
4	Bara Shigri	18.67
5	Samudra Tapu	19.90
6	Mulkila	17.47
7	Mulkila	19.40 (1980 to 2015 in Present Study)

Response of the glacier toward climatic condition depends on the thickness of glacier (Johannesson et al., 1989). Smaller glaciers retreats faster than larger one (Kulkarni et al., 2007). It can be observered from Table 4 that Panchi I, Hamtah glacier are retreating with almost equal rate but less in area than Mulkila glacier which contradicts the statement that small glacier show more climate response. It may be because in case of Hamatah glacier the accumulation area is very low, there is no source of addition of mass to the glacier (Scherler et al., 2011) it is mostly avalanche which feeds the glacier health, these both glaciers have different orientation dorection which is also important factor in the retreat of glacier. Another reason behind this contradictory retreat may be debris thickness on these two glacier, because debris plays a major role in the melting of the glacier similar conditions may be for the Panchi I glacier, while in case of Bara Shigri and Samudra Tapu glacier retreat rate is higher than Mulkila glacier because of smaller area of Mulkila . In case of Chhota Shigri and Mulkila glacier both have approximetly same area but the retreat of Chhota Shigri glacier is quiet lower than the Mulkila glacier, this may be due to high debris cover on the Mulkila glacier, different orientation which decreases the melting of the glacier and another reason may be exposure of snout. The snout of the Mulkila glacier is broad and exposed while in case of Chhota Shigri glacier snout is lies in very narrow valley and less exposed.

5.2 Area Change

Monitoring of the area change of the Mulkila glacier has been between 1980 and 2015 it has been observed from the results obtained is that there is regular decrease in the area of the glacier from 1980 to 2015. In Table 5.3 there is shown all the area of glacier.

Table 5.3 – Change in the area of Mulkila glacier from 1980 to 2015 obtained with the help of FCC made with Landsat 5 and 7 data

Year	**Area (km^2)**
1980	36.37
1989	32.25
2000	27.27
2001	28.5
2002	28.39
2003	28.25
2004	28.16
2005	26.23
2006	27.23
2007	27.23
2008	26.91
2009	26.37
2010	25.41
2011	25.32
2012	24.96
2013	24.35
2014	24
2015	23.87

1980 to 2015	**12.50**

If we consider the decadal change in the area of the glacier then from 1980 to 1989, 1989 to 2000 and 2000 to 2010 the glacier area has decreased as 4.12 km^2, 4.98 km^2 and 1.86 ±1.05 km^2. From 2010 to 2015 the change in the area is 1.54±0.66 km^2. There is a regular decrease with different rate in decades that indicates the change in climatic conditions. Maximum reduction in the area of the glacier had observed from 1980 to 1989 but the rate of decrease of the area then it is found that it is reducing with the faster rate from 2010 to 2015. Rate of shrinkage of the glacier between 1980 and 2015 is 0.25± 1.05 km^2 $year^{-1}$. Total change in the area 12.50 km^2 is estimated, which is quite large. The shrinkage of the glacier is dependent of different factors, change in area signifies for change in thickness of the glaciers which directly affects the mass balance of glacier that is significant to understand the glacier health.

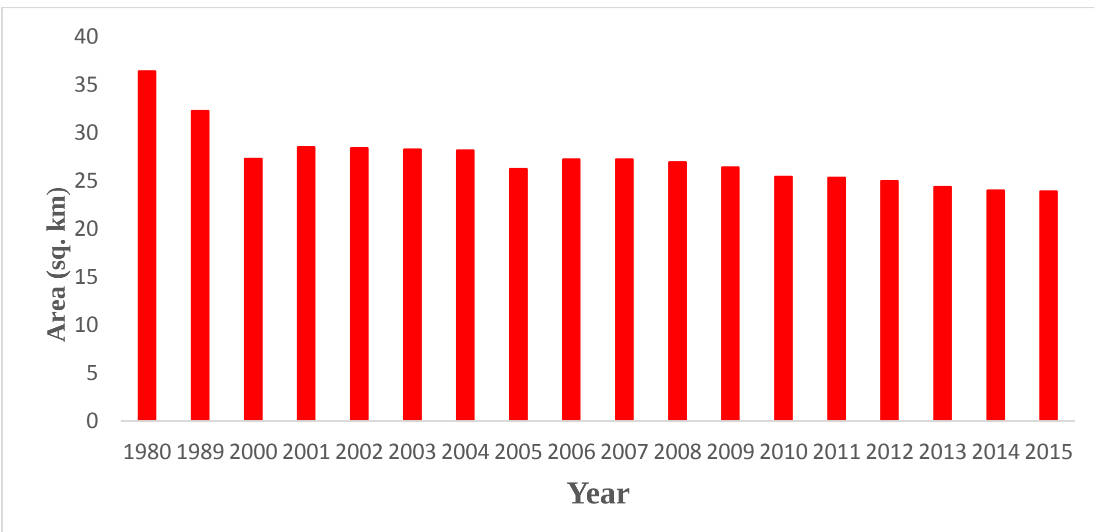

Figure 5.3- Bar diagram of Change in the area of the glacier from 1980 to 2015 with the help of Landsat.

5.3- Accumulation and ablation area change-

The change in the glacier accumulation and ablation area has been reported of the Mulkila glacier. It is very important that a continues monitoring of the change in the accumulation and ablation area should be done because it defines various property of the glacier, mass balance is one of them which is very significant in estimating the health of the any glacier. Accumulation area is the area in which there is mostly addition of the mass in occurs while in ablation area the thinning of the glacier occurs. AAR may be defined as the ratio between accumulation areas of the glacier to the total area of the glacier (Meier et al, 1962).

There is no regular pattern is observed in the accumulation area of the glacier, because it depends of the various microclimatic climatic parameters of the glacier which varies year to year, so the AAR does not have a definite pattern and it becomes a significant indicator of the glacier climate conditions. The change in accumulation, ablation and AAR has been observed from year 1980 to 2015 (Table 5.4). Between 1980 and 1989 the accumulation area has decreased approximately 20 %, it was 19 % from 1989 to 2000 which indicates the climatic conditions were not favorable for the glacier during this decade while from 2000 to 2015 the AAR changed was about 1 %. This indicates glacier mass loss was highest between 1980 and 1989, while lowest rate of mass loss is observed in the last decade.

Table 5.4- Changes reported in accumulation, ablation area and AAR of the Mulkila glacier with the help of Landsat 5 and 7 datasets.

Year	Accumulation area(km^2)	Ablation area(km^2)	AAR
1980	26.5	9.91	0.73
1989	20.47	11.81	0.63
2000	16.37	10.9	0.60
2001	15.57	13.01	0.55
2002	19.61	8.78	0.69
2003	17.2	11.23	0.61
2004	9.38	18.78	0.33
2005	9.67	16.66	0.37
2006	16.16	11.2	0.59
2007	9.92	17.31	0.36
2008	11.48	15.43	0.43
2009	18	8.51	0.68
2010	17.07	8.45	0.67
2011	14.51	11.01	0.57
2012	17.22	7.82	0.69
2013	12.6	11.75	0.52
2014	14.62	9.51	0.61
2015	16.25	7.79	0.68
Average Change (km^2year^{-1})	**-0.29**	**-0.06**	**-0.0014**

The average change in accumulation area between 1980 and 2015 is -0.29 km^2 $year^{-1}$. From the year 2000 to 2015 average accumulation area is 12.73 ± 3.18 km^2, while the rate of shrinkage of the accumulation area for the same time period is -0.008 ± 4.25 km^2 $year^{-1.}$ This shows there is quite large uncertainty in the rate of change of accumulation area per year.

The average change in the ablation area from 1980 to 2015 is -0.06 km^2 $year^{-1}$. Between 2000 and 2015 mean ablation area is 11.76 ± 3.53 km^2, which is lower than the average mean value of accumulation area for the same time period, this is helpful to understand the glacier health. Higher will be the area of accumulation more will be healthier glacier. In this glacier mean accumulation area is higher than mean ablation area for the last fifteen years of study period.

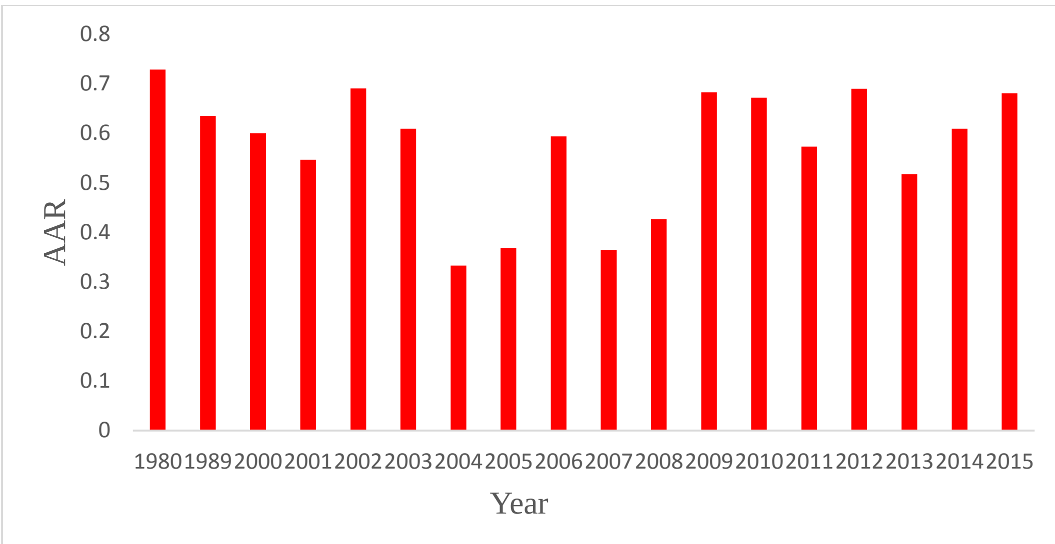

Figure 5.4 - Bar plot of change in AAR of the glacier between 1980 and 2015.

5.4 Volume Estimation –

Using different methods the volume has been estimated for different glaciers and the mean was also calculated to get an idea about the volume of the ice reserve of the glacier. These estimation are based on the basis of the area related thickness of the glacier, so the variance of the volume of the glacier fallow the somewhat same trend as that of area of the glacier. Various empirical relation as discussed previously were used and estimation is done. The study shows volume of ice reserve is decreasing with time.

Table 5.6- Estimation of volume using different methods and their mean between 1980 and 2015

Year	Method 1 Bahr et al., 1997 (km^3)	Method 2 Chen and Ohmura; 1990 (km^3)	Method 3 Bruckl et al., 1998 (km^3)	Method 4 Chaohai and Sharma; 1998 (km^3)	Mean (km^3)
1980	4.75	3.93	3.57	5.28	4.38
1989	4.03	3.34	2.99	4.50	3.72
2000	3.20	2.66	2.33	3.60	2.95
2001	3.40	2.82	2.49	3.82	3.13
2002	3.38	2.81	2.48	3.80	3.12
2003	3.36	2.79	2.46	3.78	3.10
2004	3.34	2.78	2.45	3.76	3.08
2005	3.03	2.53	2.21	3.42	2.80
2006	3.19	2.66	2.33	3.60	2.94
2007	3.19	2.66	2.33	3.60	2.94
2008	3.14	2.62	2.29	3.54	2.90
2009	3.06	2.54	2.22	3.45	2.82
2010	2.84	2.36	2.05	3.21	2.61
2011	2.74	2.28	1.98	3.10	2.52
2012	2.71	2.26	1.96	3.07	2.50
2013	2.79	2.33	2.02	3.16	2.57
2014	2.78	2.32	2.01	3.15	2.57
2015	2.77	2.31	2.00	3.14	2.56

From mean of all the methods it is estimated that the volume decreased from 1980 to 1989, 1989 to 2000 and from 2000 to 2010 is 0.66 km^3, 0.77 km^3 and 0.34 km^3 respectively. From 2010 to 2015 volume change of 0.05 km^3 has been observed. If analysis of result of different methods is considered then found that method 4 is estimating volume of the ice reserve more than any other. Least volume estimation of the glacier is by the method 3. So mean was taken to have a definite value of the ice reserve.

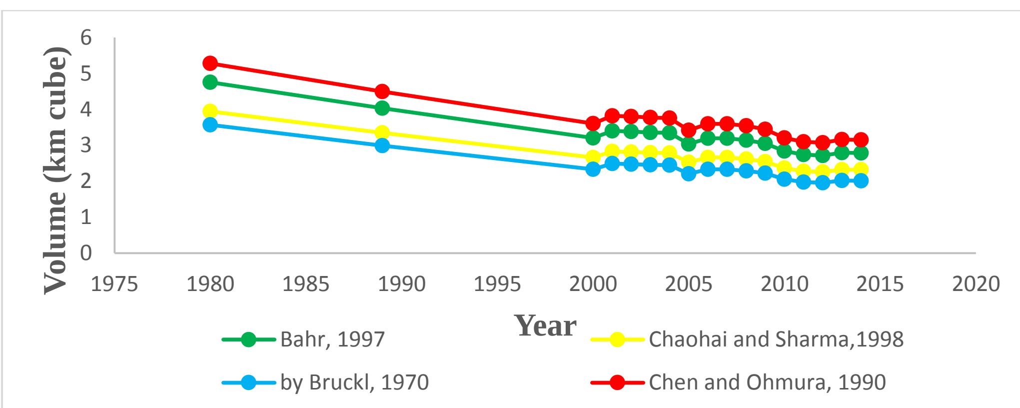

Figure 5.5- Volume change of the Mulkila glacier per year to estimate the fresh water reserve stored in form of ice estimated by different empirical realtions.

Amoung all these methods best method which could be usede to estimate the volume change of the Himalayan glacier may be the Chen and Ohmura 1990. The thickness change estimated by this method is nearest to thickness change estimated with the help DEM diffrencing. This method could be applied to other glacier in region to estimate the volume of the ice reserve. Although the uncertanity is involved in all the methods but most appropriate is Chen and Ohmra 1990 empirical relation which was applied by Frey et al., 2014.

5.5 Mass Balance of Glacier-

AAR Method-

Estimation of the mass balace was done by AAR of the glacier of different year using empirical relation as discussed earlier. These relation are showing a similar kind of pattern, but the exact values are different for different methods except Pratap et al., (2015) and Tawde et al., (2016). These to methods are showing same trend and more or less same results.

Figure 5.6 - Mass balance estimation of the glacier using various empirical relations developed using AAR for the Mulkila glacier between year 2000 to 2015.

Table 5.7- Mass balance estimated with different methods based on the AAR for year 2000 to 2015. Mean and standard deviation is also calculated for each method for this time period.

YEAR	Method 1 Kulkarni et al., (2004) (m w.e.)	Method 2 Pratap et al., (2015) (m w.e.)	Method 3 Mandal et al., (2016) (m w.e.)	Method 4 Tawde et al.,(2016) (m w.e.)
2000	0.26	-0.14	-0.12	-0.19
2001	0.13	-0.25	-0.31	-0.28
2002	0.48	0.03	0.22	-0.03
2003	0.28	-0.12	-0.08	-0.17
2004	-0.39	-0.66	-1.10	-0.65
2005	-0.31	-0.59	-0.97	-0.59
2006	0.24	-0.16	-0.14	-0.20
2007	-0.32	-0.60	-0.99	-0.60
2008	-0.17	-0.48	-0.76	-0.49
2009	0.46	0.02	0.19	-0.04
2010	0.43	-0.01	0.15	-0.06
2011	0.19	-0.20	-0.22	-0.23
2012	0.47	0.03	0.22	-0.03
2013	0.06	-0.30	-0.42	-0.33
2014	0.28	-0.13	-0.08	-0.17
2015	0.45	0.02	0.18	-0.05
Mean	**0.16±0.30**	**0.22±0.24**	**0.26±0.45**	**0.26±0.22**

Mean of all these methods was calculated for each year and its variance with the time observed ,a comparison of base line glacier mass balance obtained by calculating the average of means of mass balance of different methods to find the variance of glacier health.

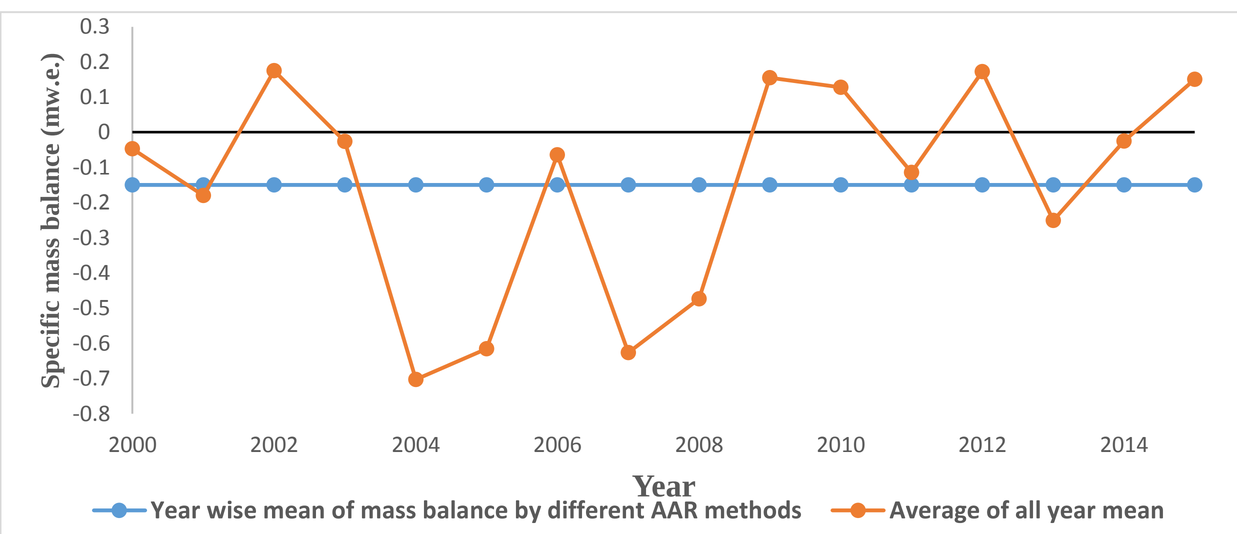

Figure 5.7 - Deviation of the year wise mean mass balance of different methods and mean of all year wise mean for Mulkila glacier from 2000 to 2015.

Figure 5.7 shows a irregular pattern in th glacier health. Health of the glacier is decresing in most of the year, but in last few year between 2009 to 2015 gain or the slightly balanced in the mass of the glacier can be observed. Maximum health loss is seen between the year 2004 and 2008. It indicated the climate condition was worse during thee time period for the glacier. It is also inferred from the figure 5.7 that AAR method is not so better method to estimate the mass balance of glaciers.

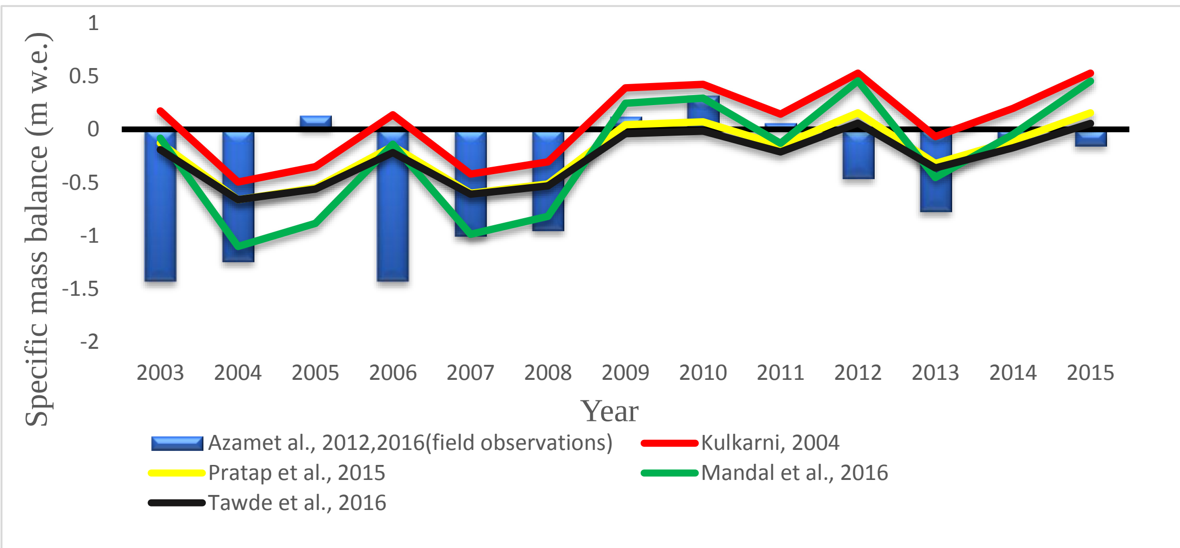

Figure 5.8- Mass balance estimation of Chhota Shigri by various AAR based equations and comparison with field observed mass balance.

These four equation are also applied to the Chhota Shigri glacier for which field mass balance data is avilable. AAR values were taken from the Azam et al., (2012, 2016). The results are showing similar trend. Field obsevations are conciding with the empirical relation developed by Azam et al., (2016), because this relation was itself derived with the field observations of the Chhota Shigri glacier. Rest of methods are showing same kind of trend but the estimated values having diffrence from the field observed mass balance data.

DEM Diffrencing (thickness change estimation) –

After proceesing of DEMs (SRTM and ASTER), diffrencing was done. ASTER GDEM of October 2011 was substracted to SRTM of February 2000. For the stable area the diffrence of these two

DEMs is 7 m which may be considered as the error assosiated with it. On the glacier this change was 2.05 m. Finally it can be inferred that elevation change between year 2000 to 2011 is about 2.05 ± 7 m. The result obtained has an error of ± 7 m. This indicates the limitation of DEM diffrencing method. The error assosiated with DEM diffrencing is mainly due to different aqusition date and diffrent satelllite sesor specifications. To minimise the error, proper orthorectification and co registration of the DEMs are required so that a better estimation of the the thickness change could be done.

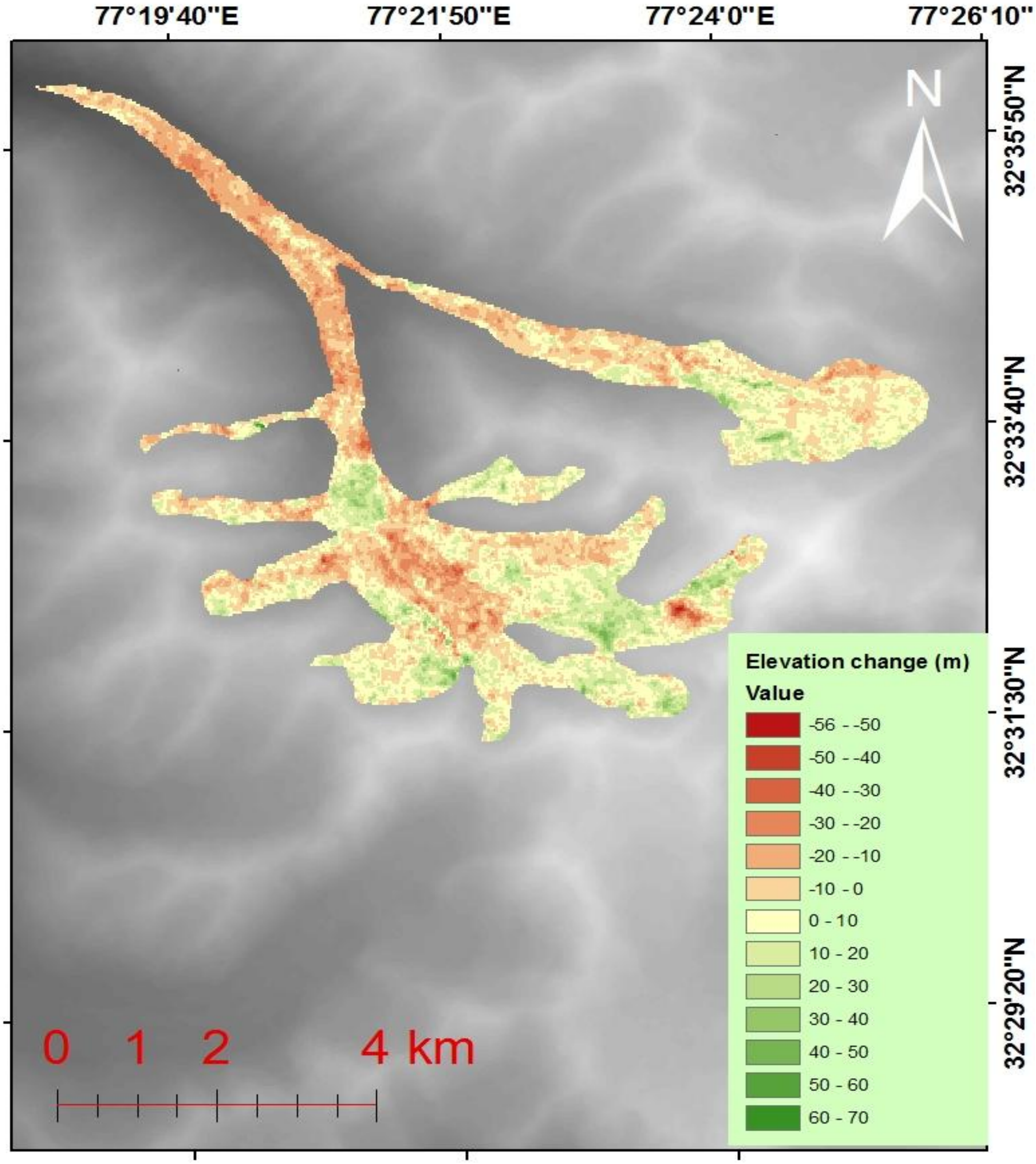

Figure 5.9-Change in the elevation 2000 to 2011 for Mulkila glacier estimated with help of DEM diffrencing of ASTER GDEM (2011) and SRTM (2000).

Several other studies has also been conducted in this region (Vijay and Braun, 2016; Vincent et al., 2013). Similar kind of result of elevation change has been obtained. Slightly more thinning is observed in the mulkila glacier region by Vijay and Braun (2016). They have also considered the penetration of C and X band of SRTM upto a certain limit, bu in case of Indian Himalayan glacier thse is need of further improvement. In present study the estimation is of the error assosisated with DEMs has been done to improve the accuracy.

5.6 Glacier Geomorphology-

Accumulation Area-

This is the area of the glacier in which mass of the glacier is incresed through snowfall with greater rate than ablation. It is the part of the glacier where the annual mass balance in a hydrological year is always positive. More will be accumulation area of the glacier, better will be the health of the glacier because more snow will contribute to health of the glacier. In case of mulkila glacier accumulation area is larger than the ablation area. According to glacier inventory of the GSI 2009 (Sangewar et al, 2009) the accumulation area of the glacier is 21.05 Km^2, while the total area of the glacier is around 28.63 km^2. Accumulation area of the glacier is roughly the 74 % of the total glacier area, but this area varies year to year depends on the micro climatic conditions of the glacier. Such a large accumulation area of glacier shows that glacier will behave in better way with respect to climate change. It will have less melting than other glacier having lesses area of accumulation.

Ablation Area-

This is the area where the mass loss the of glacier takes place. It may also be defined as the area where the melting is more than the precipitaion in the area. Melting mainly takes place in this area. If the glacier is debris covered the melting of the glacier decreses (Reznichenko et al., 2010). So we can infer that the minimum will be the glacier abltaion area and more will be it covered with debris is beneficial for the glacier health. Accrding to GSI inventory 2009 the abltaion area of the glacier is 7.58 km^2. This area is very less as compared to the accumulation area of the glacier which is good for the glacier health. It is roughly 26 % of the total area of the glacier. As in (figure 5.10) it is clear that there is high debris cover on the glacier. In the month of the June (3^{rd} June 2017) these is no snow observed on the surface of the glacier.Debris cover glaciers have different dynamics, they behave diffrently from debris free glacier because debris provide an insulation effect which affects the melting of the glacier and this effect is beneficial for the glacier health in respect of its mass balance (Wagnon et al., 2007).

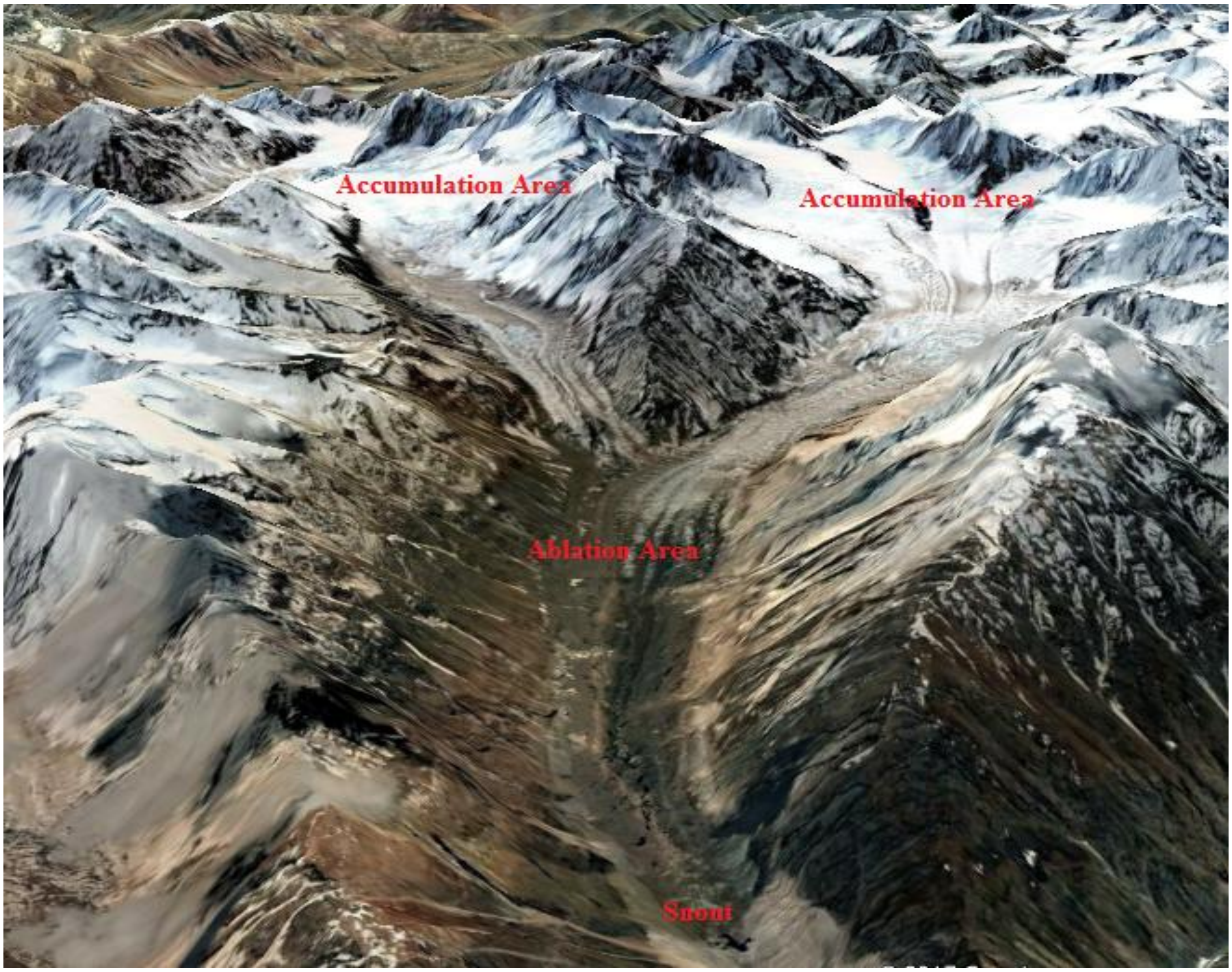

Figure 5.10- An overview of the valley of the Mulkila glacier and its accumulation, ablation area and the snout. Image source: Google Earth of 24th June 2017

Snout-

Glacier snout is also known as the glacier terminus or glacier toe. It is the lowest end of the glacier. From the snout the discharge of the glacier comes out. It is important to snout fluctuaion of the glacier takes place (Bahuguna et al., 2014). Location of the snout was reported as N $32^{0}36^{'}18.5^{''}$ and E $77^{0}18^{'}47.7^{''}$. The elevation of the snout recorded on the GPS is 3979 meters.The elevation and the position fluctuates with respect to time. It depends on the micro climatic conditions along the glacier valley. Length of snout of the Mulkila glacier is large may be because of the excess of debris on the glacier which influences the melting of the glacier and other reason may be due to the narrow valley which also infleuence the melting of the glacier.

Figure 5.11- Huge snout of the glacier and debris rich area just above the snout.Source of the debris from the valley walls. Photograph taken on 3rd June 2017 in valley of Mulkila glacier from the front of Snout. Photo Credit- Som Dutta Mishra.

Moraines-

These are a unconsolidate rock deposits formed due to depositional feature of the glacier. They are one of the important geomorphological feature of the glacier as they contains huge information about the past conditions and glacier behaviour with respect to the changing climatic conditions. They behave difrrently with advacing and retreating glacier. In other words it can be said that moraines are footprint of the glacier. There are different kind of glacier moraines depending on the pattern of retreat or advancement of the glacier some are the deposited on the margin of the glacier parallel to glacier movement are known as lateral moraine while other are terminal moraines and medial moraine which makes the boundary and the bifurcation of the glacier respectively. In present study we reported lateral moraines on the valley of glacier showing the record of the glacier and its present in past. In the field three prominent left lateral moraines were seen. On the right side of the stream another right lateral morain was there.

Figure 5.12- Right Lateral Moraines along the valley of the Mulkila glacier and the stream of glacier discharge coming from glacier valley. Photograph taken while trekking to Lungpa glacier on 4th of June 2017 . Photo Credit- Thupstan Angchuk.

Figure 5.13- Left Lateral Moraine along Mulkila glacier valley. Photo taken on 4th June 2017 while trekking toward Lungpa glacier. Photo Credit- Thupstan Angchuk

Horn-

It may be considered as the pyramodal peak of the glacier. These are formed when three or more than aretes meet at a peak. Horn generally forms sharp peak with definite edges. In the mulkila mailny three such peaks are seen with the varying elevation. Highest elevation of the peak or the Horn is of 6463 meters while rest two are of elevation 6235 and 6120 meters. There latitude and longitudes are 32^0 32' 44.17" N, 77^0 24' 42. 13" E; 32^0 32' 57. 58" N, 77^0 24' 05. 46" E and 32^0 31' 52.44" N, 77^0 23' 55.15" E respectively. These peaks forms the pyramid of the accumulation for the deposition of the snow.

Aretes-

Theses are the the rock boundary between two glaciers. They are thin and have steep slope. Generally they are U shaped in nature. It can be inferred that the aretes devide the two cirque basins of the glacier. These are a kind of erosional landform formed by the erosion of the two adjacent corries they cut the valley wall because of the movement of the glacier. In Mulkila glacier there are mainy aretes has been seen with the varying lenghts. They are forming the base wall for the cirque and the deposition of the snow and platform form for the accumulation area of the glacier.

Cirque

A cirque is a hollow, open downstream but bounded upstream by the crest of a steep slope (' headwall ') which is arcuate in plan around a more gently-sloping floor. It is glacial if the floor has been affected by glacial erosion while part of the headwall has developed sub aerially, and a drainage divide was located sufficiently close to the top of the headwall for little or none of the ice that fashioned the cirque to have flowed in from outside (Evans and Cox, 2017).

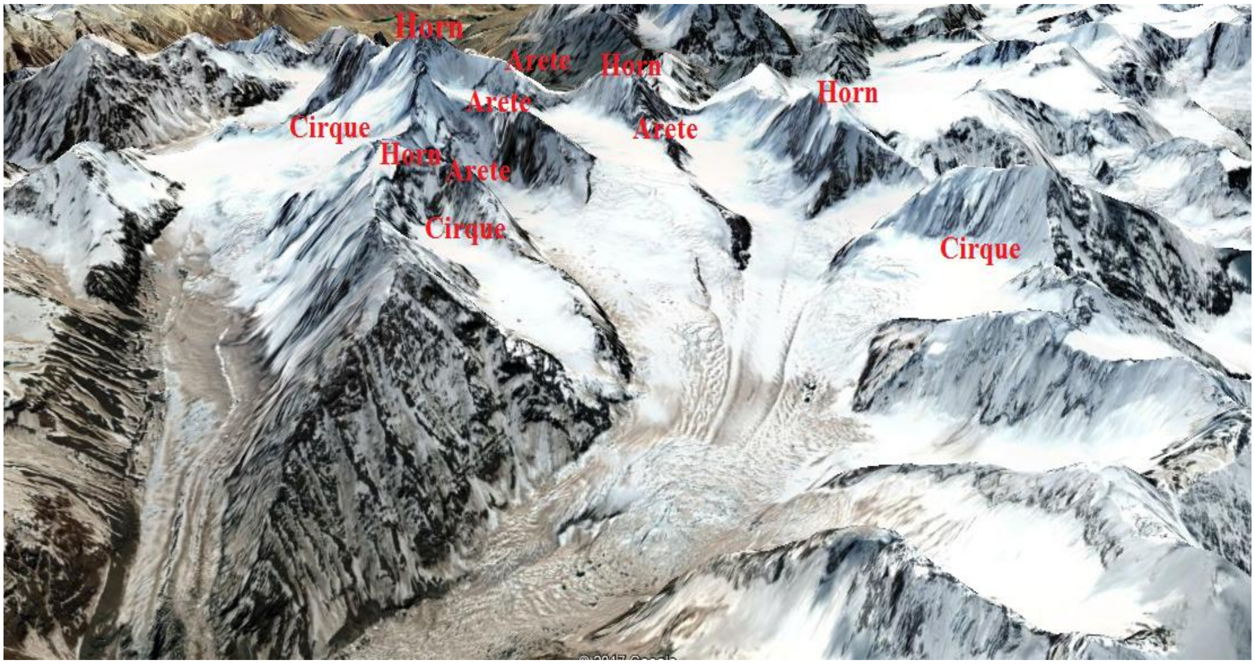

Figure 5.14- Horn, Arete and Cirque of the Mulkila glacier and the tributary if the glacier bifurcated by arete. Image source: Google Earth of 24th June 2017.

Tallus Cone-

It is a depositional kind of landform which is formed mainly by the rockfall. They are generally scree kind of deposits. There slope varies from 20^0 to 30^0 and are poorly sorted rock fragments and soil debris. Generally there is regular finnnig upward kind of trend of rock matterial along the slope. The basic confusion between alluvial cone and tallus cone is of sorting of sediment or rock fall. In case of alluvial cone a similar trend is there but the sediment are well sorted which makes them different from tallus cone. In Mulkila glacier tallus cone was seen adjacent to snout. It was clearly visible as in (Figure 5.15). Due to repetitive flow of matterial they are looking different from adjacent rock matterial as they look fresh and of bright in clour.

Other features reported in the field-

Above the snout there is a huge debris cover. The source of debris is adjacent steep rock fall, which are highly unstable and slight rainfall may trigger the derbis avlance or rock falls. There is a clear change in brightness of the rock matterial is seen above the snout in ablation zone along the valley wall which shows the position of glacier in past (Figure 5.17). Valley is very narrow and steep which provieds a platform for the debris fall and scree, because of this the terrain is large rock deposition along the valley and above the glacier.

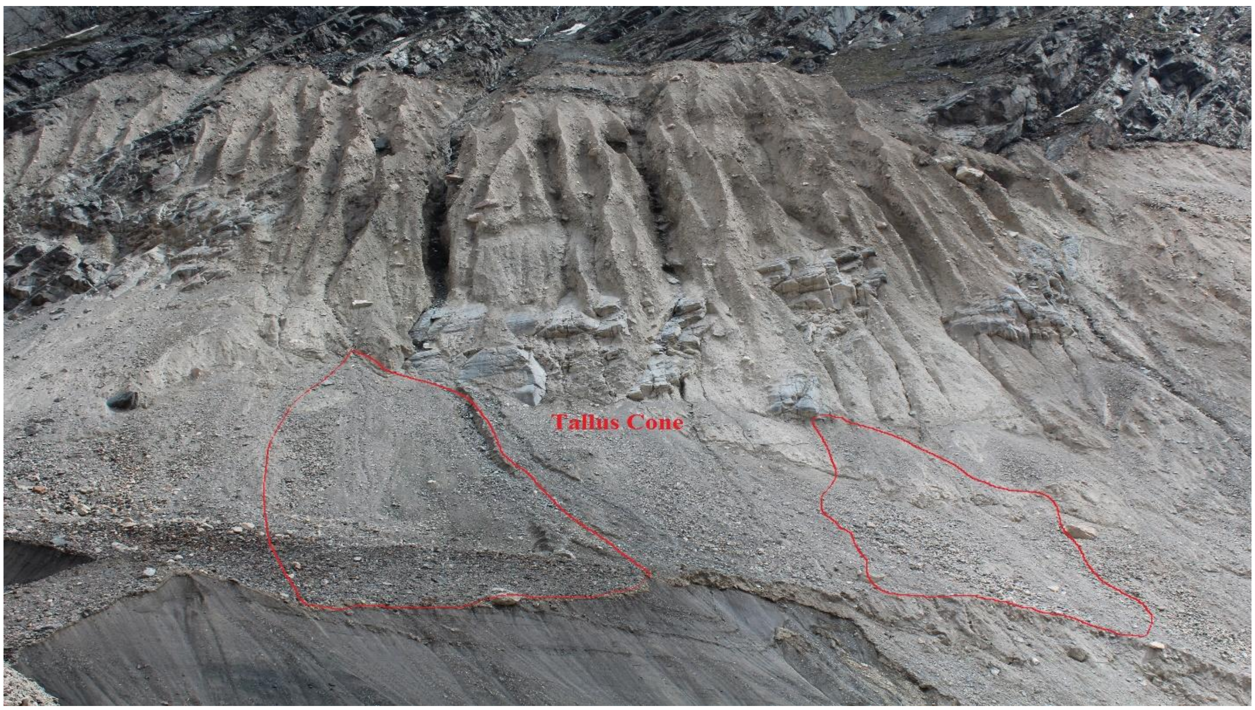

Figure 5.15- Tallus Cone just above the snout of the Mulkila glacier. Photograph taken from above the snout on 3rd June 2017. Photo credit- Thupstan Angchuk.

Figure 5.16- Field photograph showing debris cover over the snout in ablation area. Photo Credit Thupstan Angchuk on 3rd June 2017.

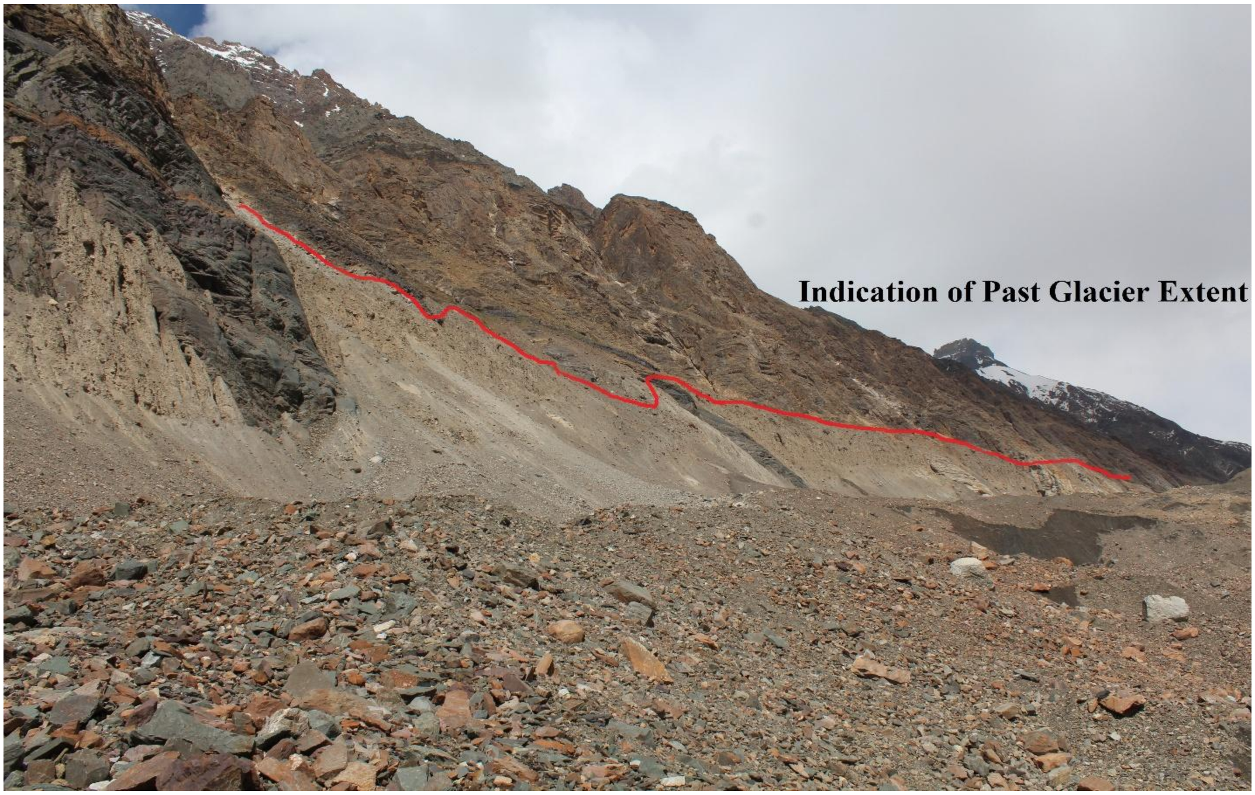

Figure 5.17- Change in colour of rock indicationg paleoglacial Extention of the Mulkila glacier. Photograph is of above the snout in ablation area. Photo credit- Thupstan Angchuk during field work on 3rd june 2017.

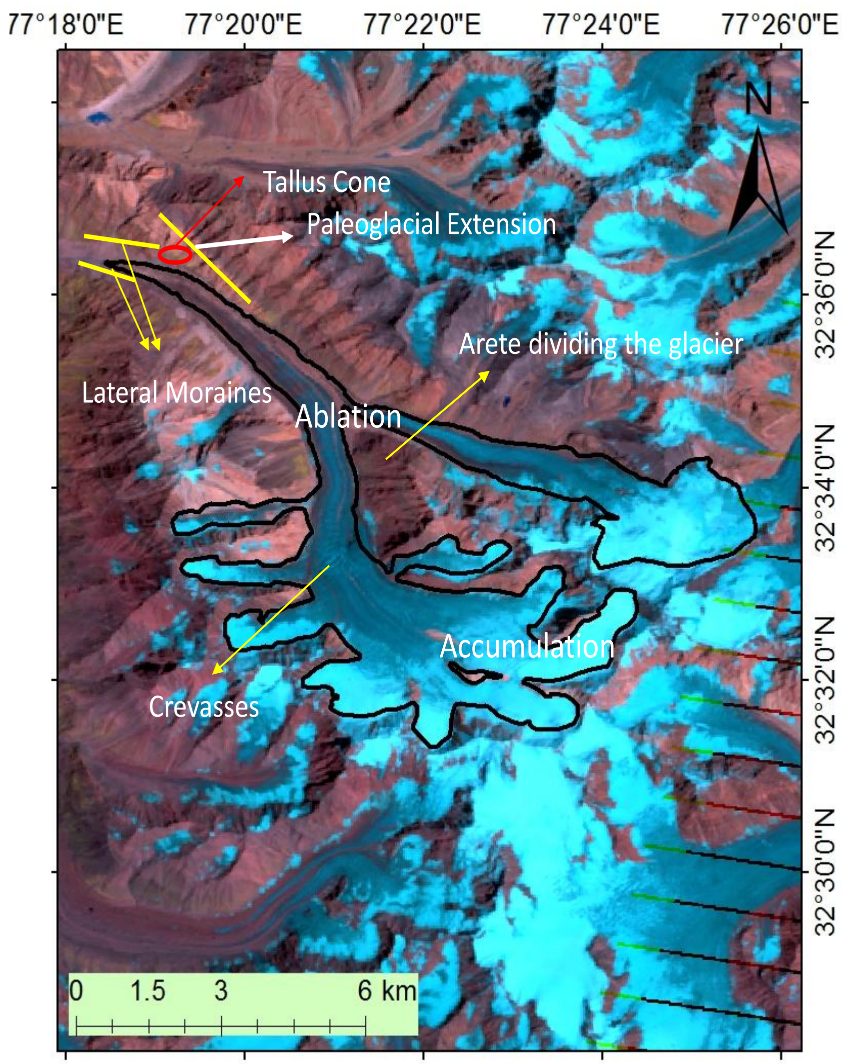

Figure 5.18- Geomorphology map of Mulkila glacier indicating the various geomorphic features identified with the help of field study and Google earth. Map is prepared with help of Landsat satellite data of 2015

Chapter 6

SUMMARY AND CONCLUSION

In this study, an attempt has been made to monitor the Mulkila glacier. Various features of the glacier were tracked during different years and a geospatial approach has been adopted to understand its dynamics. There is a dearth of data pertaining to the Himalayan glacier dynamics. Remote sensing has emerged as an important tool to fulfill this data gap partially. Continuous monitoring of the glacier is very important and it can be easily done with the help of satellite data and remote sensing.

While it has already been concluded by various researchers that the Himalayan glaciers are retreating with an alarming rate, Mulkila glacier is also being influenced by climate change, it is observed from the results obtained from the study. Snout has retreated back by 710 m with a rate of 19.40 m $year^{-1}$ during the time period of 1980 to 1989, 1989 to 2000 and 2000 to 2015. Rate of retreat is observed maximum between 2000 and 2010. Differential rate of retreat has been reported in different years because of climatic conditions which affects the western Himalayas glacier health directly. Rate of decrease in the ice volume between 1980 and 1989, 1989 and 2000 and 2000 and 2010 is estimated 0.66, 0.77 and 0.34 km^3 respectively. For the year 2010 to 2015 the change is 0.05 $km^{3.}$ The decreasing trend in the volume of the glacier since last three decades certainly influence fresh water reserve of the glacier. Decrease in volume of the glacier ice directly reflects its response to changing climatic conditions specially temperature in last decades. Increased melting of the glacier is due to its increased heating. This rate of melting may be lesser than other glaciers in the region because of high debris cover on the Mulkila glacier which has been observed in the field visit of the Mulkila glacier. There are different equations developed to estimate the volume of ice reserve of the glaciers but in this study it has been observed that equations developed by Chen and Ohmura 1990 which are used by Frey et al., 2014 is best in all of them, because the thickness change estimated by this equation is more close to the change in elevation estimated by DEM differencing. In case of AAR no regular pattern is observed, because AAR depends on the micro climatic conditions of the glacier. Average change is accumulation and ablation area is reported as - 0.29 m^2 and -0.06 km^2 in this study. For the better assessment of the AAR of any glacier the data should be of high temporal and spatial resolution. The main demerit associated with the estimation of AAR with Landsat data is that it takes the image of any area after the interval of 16 days. For better result, the data acquisition repetition should be minimum, so that any change on the glacier could be monitored. Second important factor is the spatial resolution of the data set. The resolution of the Landsat data is 30 m, there is need to obtain better spatial resolution so that error could be minimized in the estimation of AAR of the glacier.

Various AAR equations have been used to estimate the mass balance of Mulkila glacier. Different methods estimate different mass balance of the glacier. To estimate the validity of the methods, the mass balance obtained by AAR and field data is compared for Chhota Shigri glacier. It may be observed that no AAR method is predicting same values of mass balance as observed in field for Chhota Shigri glacier. Equation developed by Mandal et al., 2016 showing similar pattern because it is developed on the basis of field data of Chhota Shigri glacier itself. In case of Mulkila glacier, all the methods are estimating different mass balance. It can be concluded that no AAR method can estimate the mass balance of the glacier with accuracy. These AAR based methods can only predict the trend corresponding to the health of the glacier. All these equations are developed with field data of some glacier, so any particular equation cannot be applied to the entire Himalayan glacier. Over the Himalayas, different glaciers have different slopes and no equation has any contribution of slope in mass balance estimation with AAR methods. It is necessary to add the slope factor in the AAR equation because AAR is highly dependent on the slope of the glacier. Higher the slope of the glacier, lesser will be the AAR and vice versa. It can be concluded from the result that there is a need to improve the AAR relation to estimate the mass balance of the glacier by introducing some other factors which are governing factor to determine the accumulation area of the glacier.

In respect of DEM differencing, two main data sets are mostly used namely SRTM DEM and ASTER GDEM, these data sets are freely available and correspond to years 2000 and 2011 respectively. Quite large errors have been observed in the result. The main source of these errors lies in penetration of the C and X band of the SRTM data into the snow and ice which in turn decreases the accuracy of the result. The second source of error associated with DEM differencing is the date of acquisition of the SRTM data. It is between 10 and 20^{th} February 2000. This is the time when Himalayan glaciers are mostly covered with snow. Delineation of the actual glacier boundary and elevation difference with the help of this accumulation time data is not possible. For better result of DEM differencing, one more factor should be taken into consideration that both data should be of same season unlike ASTER GDEM and SRTM DEM which correspond to different time periods of year. Different corrections are carried out by various researchers to estimate the depth of penetration of C and X bands of SRTM but a proper depth of penetration and error associated with DEM has not been estimated with accurate precision for Indian Himalayan glaciers.

It may be concluded from the results obtained from this study that it is a necessary to carry out field study of the glaciers to understand the glacier dynamics with minimum error. All these methods based on the AAR and DEM differencing only provide an idea about the glacier health, they are not helpful in estimating exact health of the glacier. Field study is important to validate various remote sensing based studies so that they could be further applied to other glaciers of the region.

The Mulkila glacier is very diverse in its geomorphological features. Some of the prominent features in the Mulkila glacier valley include terminal moraines (Left and right both), snout, arête, horn, cirque and tallus cone. There is high debris cover on the glacier, source being the debris coming from valley walls. Snout is very large due to decreased melting of the glacier. Melting of glacier is lower may be due to the high debris cover.

The present study will be helpful in understanding the Mulkila glacier dynamics and develop further understanding after the GSI inventory. For better understanding and validation of various remote sensing techniques and results it is important to have field data. It is also important to study the meteorological condition of the region to understand glacier dynamics and its relation with climate which is lacking in study. In future it is important to install AWS in the Mulkila glacier valley to understand micro climatic parameters. Further there is need of high resolution satellite data for better understanding of the glacier.

References

Andreassen, L. M., Paul, F., Kaab, A. and Hausberg, J. E.: Landsat-derived glacier inventory for Jotunheimen, Norway, and deduced glacier changes since the 1930s, Cryosphere, 2(2), 131–145, doi:10.5194/tcd-2-299-2008, 2008.

Aniya, M., Sato, H., Naruse, R., Skvarca, P. and Casassa, G.: The Use of Satellite and Airborne Imagery to Inventory Outlet Glaciers of the Southern Patagonia Icefield , South America, , 62(12), 1361–1369, 1996.

Anon: Mass balance of Himalayan Glaciers using AAR and ELA methods, , (January 1992), doi:10.1017/S0022143000009631, 2015.

Anthwal, A., Joshi, V., Sharma, A. and Anthwal, S.: Retreat of Himalayan Galciers - Indicator of Climate Change, Nat. Sci., 4(4), 53–59, 2006.

Archer, D. R., Forsythe, N., Fowler, H. J. and Shah, S. M.: Sustainability of water resources management in the Indus Basin under changing climatic and socio economic conditions, Hydrol. Earth Syst. Sci., 14(8), 1669–1680, doi:10.5194/hess-14-1669-2010, 2010.

Arendt, A. A., Arendt, A. A., Echelmeyer, K. A., Harrison, W. D., Lingle, C. S. and Valentine, V. B.: Rapid Wastage of Alaska Glaciers and Their Contribution to Rising Sea Level, , 382(2002), doi:10.1126/science.1072497, 2006.

Azam, M. F., Wagnon, P., Ramanathan, A. L., Vincent, C., Arnaud, Y., Linda, A., Pottakkal, J. G., Chevallier, P., Azam, M. F., Wagnon, P., Ramanathan, A. L., Vincent, C. and Sharma, P.: From balance to imbalance : a shift in the dynamic behaviour of Chhota Shigri glacier , western Himalaya , India To cite this version :, , 58(208), 315–324, 2012.

Azam, M. F., Wagnon, P., Patrick, C., Ramanathan, A., Linda, A. and Singh, V. B.: Reconstruction of the annual mass balance of Chhota Shigri glacier, Western Himalaya, India, since 1969, Ann. Glaciol., 55(66), 69–80, doi:10.3189/2014AoG66A104, 2014.

Bahadur, J.: The Himalayas : A Third Polar Region, Snow Glacier Hydrol. (Proceedings Kathmandu Symp. Novemb. 1992), (218), 181–190, 1993.

Bahr, D. B.: Width and length scaling of glaciers, J. Glaciol., 43(145), 557–562, doi:10.3198/1997JoG43-145-557-562, 1997.

Bahuguna, I. M., Kulkarni, a. V., Nayak, S., Rathore, B. P., Negi, H. S. and Mathur, P.: Himalayan glacier retreat using IRS 1C PAN stereo data, Int. J. Remote Sens., 28(2), 437–442, doi:10.1080/01431160500486674, 2007.

Bahuguna, I. M., Rathore, B. P., Brahmbhatt, R., Sharma, M., Dhar, S., Randhawa, S. S., Kumar, K., Romshoo, S., Shah, R. D., Ganjoo, R. K. and Ajai: Are the Himalayan glaciers retreating?, Curr. Sci., 106(7), 1008–1013, 2014.

Bajracharya, S., Mool, P. and Shrestha, B.: The impact of global warming on the glaciers of the Himalaya, Proc. Int. Symp. Geo-disasters, Infrastruct. Manag. Prot. world Herit. sites, 231–242 [online] Available from: http://lib.icimod.org/record/12496/files/863.pdf, 2006.

Bajracharya, S. R. and Mool, P.: Glaciers , glacial lakes and glacial lake outburst floods in the Mount Everest region , Nepal Glaciers , glacial lakes and glacial lake outburst floods in the Mount Everest region , Nepal, , (February), doi:10.3189/172756410790595895, 2010.

Barry, R. G.: The status of research on glaciers and global glacier recession: a review, Prog. Phys. Geogr., 30(3), 285–306, doi:10.1191/0309133306pp478ra, 2006.

Bastiaanssen, W. G. M., Pelgrum, H., Wang, J., Ma, Y., Moreno, J. F., Roerink, G. J. and Van Der Wal, T.: A remote sensing surface energy balance algorithm for land (SEBAL): 2. Validation, J. Hydrol., 212–213(1–4), 213–229, doi:10.1016/S0022-1694(98)00254-6, 1998.

Benn, D. I. and Lehmkuhl, F.: Mass balance and equilibrium-line altitudes of glaciers in high-mountain environments, Quat. Int., 65–66, 15–29, doi:10.1016/S1040-6182(99)00034-8, 2000.

Benn, D. I., Kirkbride, M. P., Owen, L. a and Brazier, V.: Glaciated valley landsystems, Glacial landsystems, 372–406, doi:10.4324/9780203784976, 2003.

Berthier, E., Arnaud, Y., Vincent, C. and Re, F.: Biases of SRTM in high-mountain areas : Implications for the monitoring of glacier volume changes, , 33, 1–5, doi:10.1029/2006GL025862, 2006.

Berthier, E., Arnaud, Y., Kumar, R., Ahmad, S., Wagnon, P. and Chevallier, P.: Remote sensing estimates of glacier mass balances in the Himachal Pradesh (Western Himalaya, India), Remote Sens. Environ., 108(3), 327–338, doi:10.1016/j.rse.2006.11.017, 2007.

Bhambri, R., Bolch, T., Nanak, G. and College, K.: Glacier mapping : a review with special reference to the Indian Himalayas, , 33(5), 672–704, doi:10.1177/0309133309348112, 2009.

Bhambri, R., Bolch, T., Chaujar, R. K., Kulshreshtha, S. C., Bhambri, R., Bolch, T., Chaujar, R. K. and Kulshreshtha, S. C.: Glacier changes in the Garhwal Himalaya , India , from 1968 to 2006 based on remote sensing Glacier changes in the Garhwal Himalaya , India , from 1968 to 2006 based on remote sensing, , 57(203), 543–556, 2011.

Bhambri, R., Bolch, T. and Chaujar, R. K.: Frontal recession of Gangotri Glacier, Garhwal Himalayas, from 1965 to 2006, measured through highresolution remote sensing data, Curr. Sci., 102(3), 489–494, doi:10.5167/uzh-59630, 2012.

Birajdar, F. S., Venkataraman, G., Bahuguna, I. M., Samant, H. P. and Centre, S. A.: A REVISED GLACIER INVENTORY OF BHAGA BASIN HIMACHAL PRADESH , INDIA : CURRENT STATUS AND RECENT GLACIER VARIATIONS, , II(December), 9–12, doi:10.5194/isprsannals-II-8-37-2014, 2014.

Bolch, T., Buchroithner, M., Kunert, A. and Kamp, U.: Automated Delineation of Debris-Covered Glaciers Based on ASTER Data, Geoinf. Eur. (Proc. 27th EARSel Symp. 04-07 June 2007), Bozen, Italy., (June), 403–410 [online] Available from: citeulike-article-id:9343684%5Cnhttp://web.unbc.ca/~bolch/publications/BolchAl07_EARSeL-iPr.pdf, 2007.

Bolch, T., Kulkarni, A., Kääb, A., Huggel, C., Paul, F., Cogley, J. G., Frey, H., Kargel, J. S., Fujita, K., Scheel, M., Bajracharya, S. and Stoffel, M.: The State and Fate of Himalayan Glaciers EH, , (mm), 3–8, n.d.

Centre, S. A., Space, I. and Delhi, N.: SNOW AND GLACIERS OF THE HIMALAYAS :, n.d.

Change, C. and Basis, T. S.: C LIMATE C HANGE 2001 :, 2001.

Chen, J. and Ohmura, A.: Estimation of Alpine glacier water resources and their change since the 1870s, Hydrol. Mauntainous Reg., V(193), 127–136, 1990.

Das, S., Kar, N. S. and Bandyopadhyay, S.: Glacial lake outburst flood at Kedarnath, Indian Himalaya: a study using digital elevation models and satellite images, Nat. Hazards, 77(2), 769–786, doi:10.1007/s11069-015-1629-6, 2015.

Dimri, A. P., Yasunari, T., Wiltshire, A., Kumar, P., Mathison, C., Ridley, J., & Jacob, D. (2013). Application of regional climate models to the Indian winter monsoon over the western Himalayas. *Science of the Total Environment*, *468*, S36-S47.

Dyurgerov, M. B. and Meier, M. F.: Twentieth century climate change : Evidence from small glaciers, , c(Track II), 1999.

Dyurgerov, M. B. and Meier, M. F.: Year-to-Year Fluctuations of Global Mass Balance of Small Glaciers and Their Contribution to Sea-Level Changes Author (s): Mark B . Dyurgerov and Mark F . Meier Published by : INSTAAR , University of Colorado Stable URL : http://www.jstor.org/stable/155, , 29(4), 392–402, 2017.

Evans, I. S. and Cox, N.: Geomorphometry and the Operational Definition of Cirques Geomorphometry and the operational definition of cirques, , 6(2), 150–153, 2017.

Frey, H. and Paul, F.: On the suitability of the SRTM DEM and ASTER GDEM for the compilation of: Topographic parameters in glacier inventories, Int. J. Appl. Earth Obs. Geoinf., 18(1), 480–490, doi:10.1016/j.jag.2011.09.020, 2012.

Frey, H., Machguth, H., Huss, M., Huggel, C., Bajracharya, S., Bolch, T., Kulkarni, A., Linsbauer, A., Salzmann, N. and Stoffel, M.: Estimating the volume of glaciers in the Himalayan–Karakoram region using different methods, Cryosph., 8(6), 2313–2333, doi:10.5194/tc-8-2313-2014, 2014.

Guo, Z., Wang, N., Kehrwald, N. M., Mao, R., Wu, H., Wu, Y. and Jiang, X.: Temporal and spatial changes in Western Himalayan firn line altitudes from 1998 to 2009, Glob. Planet. Change, 118, 97–105, doi:10.1016/j.gloplacha.2014.03.012, 2014.

Haeberli, W., Cihlar, J. and Barry, R. G.: Glacier monitoring within the global climate observing system, Ann. Glaciol., 31(January 2016), 241–246, doi:10.3189/172756400781820192, 2000.

Hall, D. K., Foster, J. L., Irons, J. R. and Dabney, P. W.: Airborne bidirectional radiances of snow-covered surfaces in Montana, USA, Ann. Glaciol., 17(March 1991), 35–40, 1993.

Hewitt, K.: The Karakoram Anomaly? Glacier Expansion and the “Elevation Effect,” Karakoram Himalaya, Mt. Res. Dev., 25(4), 332–340, doi:10.1659/0276-4741(2005)025[0332:TKAGEA]2.0.CO;2, 2005.

Hinkel, K. M. and Nelson, F. E.: Spatial and temporal patterns of active layer thickness at Circumpolar Active Layer Monitoring (CALM) sites in northern Alaska, 1995–2000, J. Geophys. Res., 108, 1995–2000, doi:10.1029/2001JD000927, 2003.

Immerzeel, W. W., Droogers, P., de Jong, S. M. and Bierkens, M. F. P.: Large-scale monitoring of snow cover and runoff simulation in Himalayan river basins using remote sensing, Remote Sens. Environ., 113(1), 40–49, doi:10.1016/j.rse.2008.08.010, 2009.

Immerzeel, W. W., van Beek, L. P. H. and Bierkens, M. F. P.: Climate Change Will Affect the Asian Water Towers, Science (80-.)., 328(5984), 1382 LP-1385 [online] Available from: http://science.sciencemag.org/content/328/5984/1382.abstract, 2010.

Jansson, K. N. and Glasser, N. F.: Using Landsat 7 ETM+ imagery and Digital Terrain Models for mapping glacial lineaments on former ice sheet beds, Int. J. Remote Sens., 26(18), 3931–3941, doi:10.1080/01431160500106900, 2005.

Johannesson, B. T., Raymond, C. and Waddington, E. D.: TIME-SCALE FOR ADJUSTMENT OF GLACIERS TO CHANGES IN MASS BALANCE, , 35(121), 1989.

Kaab, A.: Combination of SRTM3 and repeat ASTER data for deriving alpine glacier flow velocities in the Bhutan Himalaya, Remote Sens. Environ., 94(4), 463–474, doi:10.1016/j.rse.2004.11.003, 2005.

Kääb, A.: Monitoring high-mountain terrain deformation from repeated air- and spaceborne optical data: Examples using digital aerial imagery and ASTER data, ISPRS J. Photogramm. Remote Sens., 57(1–2), 39–52, doi:10.1016/S0924-2716(02)00114-4, 2002.

Kääb, A., Wessels, R., Haeberli, W., Huggel, C., Kargel, J. S. and Khalsa, S. J. S.: Rapid ASTER imaging facilitates timely assessment of glacier hazards and disasters, Eos, Trans. Am. Geophys. Union, 84(13), 117, doi:10.1029/2003EO130001, 2003.

Kääb, A., Berthier, E., Nuth, C., Gardelle, J. and Arnaud, Y.: Contrasting patterns of early twenty-first-century glacier mass change in the Himalayas, Nature, 488(7412), 495–498, doi:10.1038/nature11324, 2012.

Kadota, T., Seko, K., Aoki, T., Iwata, S. and Yamaguchi, S.: Shrinkage of the Khumbu Glacier, east Nepal from 1978 to 1995, IAHS Publ., 264(264), 235–243, 2000.

Kaur, R., Saikumar, D., Kulkarni, A. V. and Chaudhary, B. S.: Variations in snow cover and snowline altitude in Baspa Basin, Curr. Sci., 96(9), 1255–1258, 2009.

Khromova, T. E., Osipova, G. B., Tsvetkov, D. G., Dyurgerov, M. B. and Barry, R. G.: Changes in glacier extent in the eastern Pamir, Central Asia, determined from historical data and ASTER imagery, Remote Sens. Environ., 102(1–2), 24–32, doi:10.1016/j.rse.2006.01.019, 2006.

Kulkarni, A., Patwardhan, S., Kumar, K. K., Ashok, K. and Krishnan, R.: High-resolution Regional Climate Model PRECIS Projected Climate Change in the Hindu Kush – Himalayan Region By Using the High-resolution Regional Climate Model PRECIS, Mt. Res. Dev., 33(2), 142–151, doi:http://dx.doi.org/10.1659/MRD-JOURNAL-D-12-00027.1, 2013.

Kulkarni, A. V and Rathore, B. P.: Alarming retreat of Parbati glacier , Beas basin , Himachal Pradesh, , 88(11), 2005.

Kulkarni, A. V, Bahuguna, I. M., Rathore, B. P., Singh, S. K., Randhawa, S. S., Sood, R. K. and Dhar, S.: Glacial retreat in Himalaya using Indian Remote Sensing satellite data, , 69–74, 1962.

Kulkarni, A. V., Rathore, B. P., Singh, S. K. and Bahuguna, I. M.: Understanding changes in the Himalayan cryosphere using remote sensing techniques, Int. J. Remote Sens., 32(3), 601–615, doi:10.1080/01431161.2010.517802, 2011.

Luckman, B. H. and Villalba, R.: Assessing the Synchroneity of Glacier Fluctuations in the Western Cordillera of the Americas During the Last Millennium, 2001.

Mandal, A., Ramanathan, A. L., Angchuk, T. and Soheb, M.: Unsteady state of glaciers (Chhota Shigri and Hamtah) and climate in Lahaul and Spiti region , western Himalayas : a review of recent mass loss, Environ. Earth Sci., 1–12, doi:10.1007/s12665-016-6023-5, 2016.

Meier, M. F. and Dyurgerov, M. B.: THE HEALTH OF GLACIERS : RECENT CHANGES IN GLACIER REGIME, , 123–135, n.d.

Messerli, B., Viviroli, D. and Weingartner, R.: Mountains Vulnerable of the World : Water Towers for the 21st Century, AMBIO Spec. Rep., 13(December 2004), 29–34, doi:10.5167/uzh-110516, 2004.

Moors, E. J., Groot, A., Biemans, H., Van Scheltinga, C. T., Siderius, C., Stoffel, M., Huggel, C., Wiltshire, A., Mathison, C., Ridley, J., Jacob, D., Kumar, P., Bhadwal, S., Gosain, A. and Collins, D. N.: Adaptation to changing water resources in the Ganges basin, northern India, Environ. Sci. Policy, 14(7), 758–769, doi:10.1016/j.envsci.2011.03.005, 2011.

Napieralski, J., Hubbard, A., Li, Y., Harbor, J., Stroeven, A. P., Kleman, J. and Jansson, K. N.: Towards a GIS assessment of numerical ice-sheet model performance using geomorphological data, , 53(180), 71–83, 2007.

Nuth, C. and Kääb: Co-registration and bias corrections of satellite elevation data sets for quantifying glacier thickness change, Cryosphere, 5(1), 271–290, doi:10.5194/tc-5-271-2011, 2011.

Oerlemans, J.: Extracting a climate signal from 169 glacier records., Science, 308(5722), 675–7, doi:10.1126/science.1107046, 2005.

Owen, L. A., Gualtieri, L. Y. N., Finkel, R. C., Caffee, M. W., Benn, D. I. and Sharma, M. C.: Cosmogenic radionuclide dating of glacial landforms in the Lahul Himalaya , northern India : defining the timing of Late Quaternary glaciation, , 16, 555–563, doi:10.1002/jqs.621, 2001.

Pandey, P. and Venkataraman, G.: Changes in the glaciers of Chandra–Bhaga basin, Himachal Himalaya, India, between 1980 and 2010 measured using remote sensing, Int. J. Remote Sens., 34(15), 5584–5597, doi:10.1080/01431161.2013.793464, 2013.

pati Ray, P. K., Chattoraj, S. L., Bisht, M. P. S., Kannaujiya, S., Pandey, K. and Goswami, A.: Kedarnath disaster 2013: causes and consequences using remote sensing inputs, Nat. Hazards, 81(1), 227–243, doi:10.1007/s11069-015-2076-0, 2016.

Paul, F., Kääb, A., Maisch, M., Kellenberger, T. and Haeberli, W.: Rapid disintegration of Alpine glaciers observed with satellite data, Geophys. Res. Lett., 31(21), 12–15, doi:10.1029/2004GL020816, 2004.

Paul, F., Barrand, N. E., Baumann, S., Berthier, E., Bolch, T., Casey, K., Frey, H., Joshi, S. P., Konovalov, V., Le Bris, R., Mölg, N., Nosenko, G., Nuth, C., Pope, A., Racoviteanu, A., Rastner, P., Raup, B., Scharrer, K., Steffen, S. and Winsvold, S.: On the accuracy of glacier outlines derived from remote-sensing data, Ann. Glaciol., 54(63), 171–182, doi:10.3189/2013AoG63A296, 2013.

Pfeffer, W. T., Arendt, A. A., Bliss, A., Bolch, T., Cogley, J. G., Gardner, A. S., Hagen, J. O., Hock, R., Kaser, G., Kienholz, C., Miles, E. S., Moholdt, G., M??lg, N., Paul, F., Radi??, V., Rastner, P., Raup, B. H., Rich, J., Sharp, M. J., Andreassen, L. M., Bajracharya, S., Barrand, N. E., Beedle, M. J., Berthier, E., Bhambri, R., Brown, I., Burgess, D. O., Burgess, E. W., Cawkwell, F., Chinn, T., Copland, L., Cullen, N. J., Davies, B., De Angelis, H., Fountain, A. G., Frey, H., Giffen, B. A., Glasser, N. F., Gurney, S. D., Hagg, W., Hall, D. K., Haritashya, U. K., Hartmann, G., Herreid, S., Howat, I., Jiskoot, H., Khromova, T. E., Klein, A., Kohler, J., K??nig, M., Kriegel, D., Kutuzov, S., Lavrentiev, I., Le Bris, R., Li, X., Manley, W. F., Mayer, C., Menounos, B., Mercer, A., Mool, P., Negrete, A., Nosenko, G., Nuth, C., Osmonov, A., Pettersson, R., Racoviteanu, A., Ranzi, R., Sarikaya, M. A., Schneider, C., Sigurdsson, O., Sirguey, P., Stokes, C. R., Wheate, R., Wolken, G. J., Wu, L. Z. and Wyatt, F. R.: The randolph glacier inventory: A globally complete inventory of glaciers, J. Glaciol., 60(221), 537–552, doi:10.3189/2014JoG13J176, 2014.

Pratap, B., Prasad, D., Rakesh, D. and Manish, B.: Four decades of glacier mass balance observations in the Indian Himalaya, Reg. Environ. Chang., doi:10.1007/s10113-015-0791-4, 2015.

Racoviteanu, A. E., Arnaud, Y., Williams, M. W. and Ordon, J.: Decadal changes in glacier parameters in the Cordillera Blanca , Peru , derived from remote sensing, , 54(186), 499–510, 2008a.

Racoviteanu, A. E., Williams, M. W. and Barry, R. G.: Optical remote sensing of glacier characteristics: A review with focus on the Himalaya, Sensors, 8(5), 3355–3383, doi:10.3390/s8053355, 2008b.

Ramanathan, A.: Status Report on Chhota Shigri Glacier (Himachal Pradesh), Dep. Sci. Technol. Minist. cience Technol. New Delhi, Himal. Glaciol. Rep. No. 1., (1), 88p., 2011.

Raup, B., Racoviteanu, A., Khalsa, S. J. S., Helm, C., Armstrong, R. and Arnaud, Y.: The GLIMS geospatial glacier database: A new tool for studying glacier change, Glob. Planet. Change, 56(1–2), 101–110, doi:10.1016/j.gloplacha.2006.07.018, 2007.

Ray, M. and Sreedhar, R.: Climate Vulnerability in North Western Himalayas, 2011.

Ren, J., Jing, Z., Pu, J. and Qin, X.: Glacier variations and climate change in the central Himalaya over the past few decades, Ann. Glaciol., 43(1), 218–222, doi:10.3189/172756406781812230, 2006.

Reznichenko, N., Davies, T., Shulmeister, J. and Mcsaveney, M.: Effects of debris on ice-surface melting rates : an experimental study, , 56(197), 384–394, 2010.

Rignot, E. and Echelmeyer, K.: Penetration depth of interferometric synthetic‐aperture radar signals in snow and ice, , 28(18), 3501–3504, 2001.

Rodríguez, E., Morris, C. S. and Belz, J. E.: A Global Assessment of the SRTM Performance, , 72(3), 249–260, 2006.

Sangewar, C. V, Shukla, S. P. and Singh, R. K.: Inventory of the Himalayan glaciers, 2009.

Scherler, D., Bookhagen, B. and Strecker, M. R.: Spatially variable response of Himalayan glaciers to climate change affected by debris cover, Nat. Geosci., 4(3), 156–159, doi:10.1038/ngeo1068, 2011.

Schiefer, E., Menounos, B. and Wheate, R.: Recent volume loss of British Columbian glaciers , Canada, , 34(May), 1–6, doi:10.1029/2007GL030780, 2007.

Seidel, K., Ehrler, C., Martinec, J. and Turpin, O.: Derivation of statistical snow line from high resolution snow cover mapping, EARSeL Work. L. Ice Snow, (July), 1–6, 1997.

Shehmani, Dharpure, J. K., Kochhar, I., Ram, R. P. H. and Ganju, A.: Analysis of snow cover and climatic variability in Bhaga basin located in western Himalaya, Geocarto Int., 6049(May 2016), 1–14, doi:10.1080/10106049.2015.1120350, 2015.

Shekhar, M. S., Chand, H., Kumar, S., Srinivasan, K., & Ganju, A. (2010). Climate-change studies in the western Himalaya. *Annals of Glaciology*, *51*(54), 105-112.

Shilts, W. W.: Geological Survey of Canada's contributions to understanding the composition of glacial sediments, Can. J. Earth Sci., 30(2), 333–353 [online] Available from: http://www.scopus.com/inward/record.url?eid=2-s2.0-0027876999&partnerID=40&md5=5db1c32cb902996abee90993e898e295, 1993.

Solomina, O., Haeberli, W., Kull, C. and Wiles, G.: Historical and Holocene glacier-climate variations: General concepts and overview, Glob. Planet. Change, 60(1–2), 1–9, doi:10.1016/j.gloplacha.2007.02.001, 2008.

Surazakov, A. B. and Aizen, V. B.: Estimating Volume Change of Mountain Glaciers Using SRTM and Map-Based Topographic Data, , 44(10), 2991–2995, 2006.

Tulaczyk, S., Kamb, B., Scherer, R. P. and Engelhardt, H. F.: Sedimentary processes at the base of a West Antarctic ice stream; constraints from textural and compositional properties of subglacial debris, J. Sediment. Res., 68(3), 487–496, doi:10.2110/jsr.68.487, 1998.

Vijay, S. and Braun, M.: Elevation change rates of glaciers in the Lahaul-Spiti (Western Himalaya, India) during 2000-2012 and 2012-2013, Remote Sens., 8(12), 1–16, doi:10.3390/rs8121038, 2016.

Vincent, C., Ramanathan, A., Wagnon, P., Dobhal, D. P., Linda, A., Berthier, E., Sharma, P., Arnaud, Y., Azam, M. F., Jose, P. G. and Gardelle, J.: Balanced conditions or slight mass gain of glaciers in the Lahaul and Spiti region (northern India, Himalaya) during the nineties preceded recent mass loss, Cryosph., 7(2), 569–582, doi:10.5194/tc-7-569-2013, 2013.

Viviroli, Daniel; Messerli, B.: Assessing the Hydrological Significance of the World's Mountains, Mt. Res. Dev., 23(4), 369–375, doi:10.1659/0276-4741(2003)023, 2003.

Wagnon, P., Linda, A., Arnaud, Y., Kumar, R., Sharma, P., Vincent, C., Pottakkal, J. G., Berthier, E., Ramanathan, A., Hasnain, S. I. and Chevallier, P.: Four years of mass balance on Chhota Shigri Glacier , Himachal Pradesh , India , a new benchmark glacier in the western Himalaya, , 53(183), 603–611, 2007.

Yale, T., Journal, L., The, S., Law, Y., April, N., Yale, T., Journal, L. and Purdy, J.: The Politics of Nature : Climate Change , Environmental Law , and Democracy, , 119(6), 1122–1209, 2017.

Zemp, M., Haeberli, W., Hoelzle, M. and Paul, F.: Alpine glaciers to disappear within decades?, Geophys. Res. Lett., 33(13), 6–9, doi:10.1029/2006GL026319, 2006.