EVALUATION AND CUSTOMIZATION OF GLACIER MASS BALANCE IN GEOSPATIAL ENVIRONMENT

Thesis submitted to the Andhra University, Visakhapatnam in partial fulfillment of the requirement for the award of

Master of Technology in Remote Sensing and GIS

ANDHRA UNIVERSITY

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CERTIFICATE

This is to certify that Ms. Mansi Puri has carried out her Project entitled "Evaluation and Customization of Glacier Mass balance in Geospatial Environment", in partial fulfillment of the requirement for the Master of Technology in Remote Sensing and GIS at Indian Institute of Remote Sensing (IIRS) during August 2011- August 2013. The work has been carried out under the supervision of Dr. Praveen Kumar Thakur 'Scientist – SE', Water Resource Department, IIRS, ISRO and Dr. Vaibhav Garg 'Scientist- SD', Water Resource Department, IIRS, ISRO.

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ACKNOWLEDGEMENTS

It is my indeed pleasure to express my deepest gratitude to Dr. Y.V. N. Krishna Murthy, Director IIRS for providing excellent research environment, motivation, support to carry out this research work. I would like to gratefully acknowledge Dr. S.P. Aggarwal, Scientist ‘SF’, Head Water Resources Department and Dr. S.K. Saha, Scientist ‘SG’ and Group Director Earth Resources and System Studies and Dean Academics for giving valuable suggestions and evaluating our research project time to time and encourage our spirits to work in a right direction successfully.

I take this opportunity to express my deep and profound sense of respect and heartfelt thanks to my supervisor Mr. Praveen Kumar Thakur, Scientist /Engr. ‘SE’ for providing his expert guidance, impeccable advises for solving problem, inspiration and support throughout project work. His constant and timely supervision and encouragement helped me a lot in completing my project work at right time.

I would like to give my sincere thanks to Dr. Bhaskar R. Nikam, Scientist ‘SD’, Dr. Viabhav Garg, Scientist ‘SD’, Mr. Arpit Chouksey, Scientist ‘SC’ Water Resources Department IIRS Dehradun for providing valuable suggestions to improve my project and representation skills.

I would also like to give heartfelt gratitude to Mrs. Shefali Aggarwal, Scientist ‘SF’ and M.Tech, course coordinator for scheduling and coordinating our M.Tech Project.

I would like to thanks Andhra University who give me opportunity to pursue this course.

I have been highly motivated and supported by all my friends during my project work in IIRS. I would like to give Special thanks to Mr. Rashmit Singh Sukhmani Scientist ‘SC’, Anupriya, Sivi, Ben, Taibang, Joyson, and Moa for immense cooperation and establishing friendly and homely environment for me to live in IIRS. I would like to give sincere thanks to my M. Tech classmates Anudeep, Tarul, Rajtantra and Suman.

I would like to dedicate this M.Tech thesis to my amazingly loving and supportive parents and elder Brother and Sister who have always been with me and encourage paving my way out in difficult situation.

At last I express my deep love to this institute and gratefulness to all the faculties who imparted me each and every bit of their valuable knowledge

Place: - Dehradun

Date: - 19 August 2013 Mansi Puri

ABSTRACT

Glaciers are the fresh water source of India which is showing a continuous change in their area and volume. But the change is not spatially or temporally uniform. As per the literature review most of the Indian Himalayas are retreating due to climate change. So, it is necessary to monitor the status or health of Glaciers. The most viable and important parameter which show glacier health is the Mass balance. Change in the mass balance easily access that whether glacier are advancing or retreating depending value of mass balance. This study focus on Estimation of Glacier Mass balance by two methods Accumulation Area Ratio Method and Geodetic Method for monitoring change in glacier with the help remote sensing. This study establishes a mathematical model among the actual mass balance , total glacier extent and accumulation area collected in between 2002-2010 on Chhota Shigri Glacier, which result as a linear relationship x= 0.0386*y – 2.5007, where x = mass balance and y = AAR. With the coefficient of correlation R^2 = 0.95. The study also deals with mapping of Accumulation and Ablation zone with Optical, Thermal and Microwave Remote Sensing, using NDSI, NDSTI, Band Ratio, LST and Backscattering value which further used to calculate AAR and r mass balance of glaciers over a time series. The actual and satellite derived mass balance are comparable and shows good correlation. The value of AAR ranges between 0.29 to 0.72. The mass balance also ranges in between -1.4 m w.e and 0.25 m w.e. This study gives an RMSE error of 0.038 of mass balance evaluated through actual and remote sensing data.

In Geodetic Method, One DEM generated from Base map of 40 meter contour interval and another DEM from SRTM resample at 30 meters are used to generate a height difference map which is then converted into mass balance in water equivalent. The Mass balance is calculated over 36 years (1966-2002) has average positive value of 0.30±1.67m w.e.yr^{-1}.

This study also focus on the customization of Mass balance by both geodetic and AAR method in terms of open source image processing tool which will provide an aid to estimate Mass balance independently as there is need to map and estimate the glacier mass balance to understand the climate variability. Since very less work on glacier has been done till now. To ease somewhat manual work of image processing python is chosen to be one of the programming languages so that non programmer can understand the process. The Results obtained from tool is comparable and matching with the processing done with other Image processing software.

Keywords: - AAR - Accumulation Area Ratio, ELA – Equilibrium Line Altitude, NDSI – Normalized Difference Snow Index, NDSTI – Normalized Difference Snow Thermal Index, LST – Land Surface Temperature.

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1. INTRODUCTION

"Glaciers are delicate and individual things like Human. Instability is built in them."

By Will Harrison

1.1 Evolution of Glaciers

The major land form that has confronted a long term change from ice age i.e. Pleistocene era is mainly frozen form of water. These frozen form of water covered around one third percent of total world's land mass around 2.5 million years ago which now get reduced to 10 percent and are present in the form of Glaciers, snow, ice caps, sea ice, ice sheets. Glaciers are considered to be coolers of world and one of the natural fresh water resources. Presently, it has been reported that glaciers cover around 15,000,000km^2 of area globally, out of which more than 14,000,000km^2 area are flanked by the two major continents Greenland and Antarctica. While the rest of the glacier cover are dispersed within the mountains of Alps, Rockies, The Himalayas and New Zealand Alps in the Northern Hemisphere. These glaciers are distributed so far and wide that they don't have any specific latitudinal, longitudinal as well as climatic zones. Due to this reason variations and fluctuations are observed in the nature, number and response of basins lying under these regions. These fluctuations are supposed to be the straight forward issues of the periodic instability (Raina, 2009).

The process of formation of Himalayan glaciers is the consequence of ice age i.e. Pleistocene age which is around two million years to till now. However glaciations was not a continuous event; there were alternate phases of cold climate with accumulation of snow ice cover and its advance with periods of warm climate with ablation and ice degeneration. Many great Glaciologists believe that there may have been around 21 glacial cycles during the last ice age, alternating with interglacial warm periods. Present era is also attributed to interglacial warm period, and has been considered to be the period of glacier retreat. (Raina, 2009)

1.2 Glacier: Fresh water source

Glaciers are considered as the fresh water source and the lifeline of majority of major rivers of world on the earth. The distribution of water resources on earth showing that there is only 2.5% of fresh water in the form of glaciers and ice caps, ground water and surface fresh water which is needed for life to sustain. Out of which 68.6% of fresh water are locked in the form glaciers and ice caps and which is around 1.74% of the total global water (http://ga.water.usgs.gov/edu/watercyclesummary.html). The fig 1.1 shows the distribution of water on the earth surface.

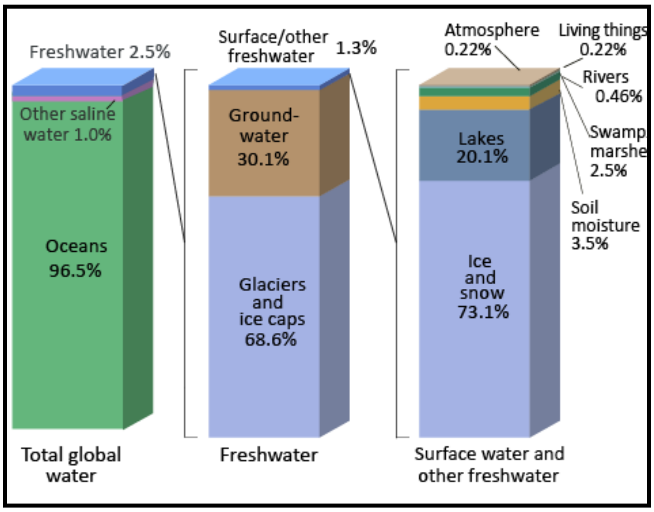


***Figure 1.1**: Total water distribution of the earth. (**Source**: Gleick, 1996)*

The distribution of other source of water in cubic kilometres and as well as their percent has been tabulated in table1.1.

***Table1.1:** Quantitative amount and percent of fresh water present on earth.*
*(**Source**:* Gleick, 1996)

Water source	*Water volume, in cubic miles*	*Water volume, in cubic kilometres*	*Percent of freshwater*	*Percent of total water*
Oceans, Seas, & Bays	321,000,000	1,338,000,000	0%	96.5
Icecaps, Glaciers, & Permanent Snow	5,773,000	24,064,000	68.6%	1.74
Ground water	5,614,000	23,400,000	30.1%	1.7
Soil Moisture	3,959	16,500	0.05	0.001
Ground Ice & Permafrost	71,970	300,000	0.86	0.022
Lakes	42,320	176,400	0%	0.013
Fresh	21,830	91,000	0.26	0.007
Saline	20,490	85,400	0%	0.007
Atmosphere	3,095	12,900	0.04	0.001
Biological Water	269	1,120	0.003	0.0001
Swamp Water	2,752	11,470	0.03	0.0008

1.3 Glacier distribution in India

After the Arctic Greenland/ and Antarctic region, Hindu Kush Himalayas range has the third largest ice mass and is the biggest mountain range on earth, known to be as ‘Third pole’ which covers around 59000km^2 area out of total world’s area of 540000km^2 (Dyurgerov and Meier, 2005). Looking over its extent on the countries of Afghanistan, Pakistan, India, Bangladesh, Bhutan, Nepal, China and Myanmar, it covers approximately 4,192,000km^2 over mountainous area. Because of rugged terrain, diverse climate, different ecology and tectonics activity HKH region is considered to be one of sensitive, fragile, most dynamic as well as complex world's mountain systems. (Bajracharya.*et.al* 2011).The melt water from snow and glaciers of HKH region feeds about 10 largest rivers system in whole Asia and support large population living in downstream areas. Among Hindu Kush Himalayas range, Himalayas has largest range of young mountains. It is also known as water tower of Asia as it contains large number of water of perennial snow and ice at the highest elevation. Basically Himalayas spread between 27° – 35°N latitude and 74° – 96°E longitude. According to the recent report based on glacier inventory presented by the Geological Survey of India there are around 9,575 glaciers are found to be present in the Indian administered part of the Himalaya in the dominion of Uttarakhand, Himachal Pradesh, Jammu and Kashmir, Sikkim and Arunachal Pradesh (Sangewar and Shukla, 2009) covering area within these states is of approximately 37466 km^2 area (Raina and Srivastava, 2008). The glaciers of great Indian Himalayas are the valuable national as well as global asset possesses largest resources of snow and ice outside the Polar Regions, feeding almost all main, major minors rivers and tributaries of north India.

The major river basin of Indus, Ganga and Brahmaputra when put together convey that these have total 32392 number~~s~~ of glaciers covering around 71182.08km^2 area are found in these river basins. Basin wise number of glaciers as well as area covered has been summarized in table 1.2. and shows that it shows that Indus Basin has around 16049 glaciers occupying 32246.43km^2 area. The Ganga basin occupying 18392.90 km^2 of area covering around 6237 glaciers. The Brahmaputra basin contains 10106 glaciers which spread in 20542.75 km^2 of glaciated area (Ramanathan, 2011).

Table 1.2: *Number of Glaciers found in Indus, Ganga and Brahmaputra Basin*

Name of the Basin	***Number of Glaciers***	***Area of Glacier***
Indus basin	16049	32246.43km^2
Ganga basin	6237	18392.90 km^2
Brahmaputra	10106	20542.75 km^2
Total	***32392***	***71182.08km^2***

The demand for fresh water has risen up to four-times since 1940 as a result of increasing population, intensifying agriculture, expanding urbanization and industrialization. Glaciers play very important role in understanding the variations in our environment. More specifically glaciers are known to be best indicator of changing climate. Glaciers nowadays are showing continuous change in their area and volume, so any change in the shape and size of glaciers directly affect the hydrology of low lying areas .In many parts of the world, water distribution in the rivers is seasonal, which shows a high runoff in rainy season, while during the rest of year, it remain dry. In this dry spell, mountain glaciers are only source which provide water to these dry rivers. (SAC, 2010).

The Great Indian Himalayas shows a high variability in precipitation in the different ranges. The North-Western Himalayas receive around 100 to 1600 cm of snowfall across different ranges (Bhutiyani *et al*., 2009). It has been estimated that runoff generated from glacier melt and snow melt is around 5% of the rainfall of the country. (Ramanathan, 2011). Considering the importance of glaciers and ice-caps, the volume and expansion of ice of Himalayan region is of high interest at present and for future climatic conditions. Understanding the climatic condition of Himalayan region of past and present times, it gives an important observation in the actual manifestation of climate change. So, it is our foremost duty to know the importance of glaciers in terms of changing global climate (SAC, 2010). As per the latest report published in 2011 by the International Centre for Integrated Mountain Development (ICIMOD), Glaciers of central and eastern Himalayas are appear to be shrinking due to loss in glacier extend and mass balance So, in order to maintain the sustainability of the glacier, which is a vulnerable source of fresh water and for the sake of water security of India it is important to monitor and assess the health or state of the glacier periodically.

Before going into deep discussion into the mass balance studies, it would be needed to know about glaciers and its main characteristics.

1.4 What are Glaciers?

Meier (1994) gave scientific definition of glacier as “a body of ice originating on land by the re-crystallization of snow or other form of solid precipitation and showing evidence of past and present flow” but in general terms the word glacier has been coined from the Latin word “glacis” which means Ice. Another definition given by knight (1999) for glacier as “a huge mass of ice slowly flowing over a land mass, formed from compacted snow in an area where snow accumulation exceeds melting and sublimation”. A glacier is a large permanent mass of ice, consisting mainly of re-crystallization of snow and rock debris that accumulate in and moves slowly outwards or downwards due to the stress of their sheer mass under the effect of gravity. Glaciers can carve out the land and change landscapes. The effect of glacier is limited to local climatic conditions and considered to be good regional climatic indicator (Lepparanta & Granberg, 2010). Glaciers are formed when the accumulation of snow exceeds than the melting in summer season. The main principle for the glacier presence over a region is that winter snowfall should be sufficiently high and the temperature should not be more than 0°C. Due to the presence of excessive snowfall and snow accumulation during consecutive years, glaciers usually tend to form in extreme cold and wet regions (Kuhn, 2010). Glaciers usually contain dirt impurities. They enclose atmospheric gases and particles at top surface and rock particles at the bottom surface and side boundaries (Lepparanta & Granberg, 2010).

1.4.1 Glacier formation

Glaciers are formed when snow that accumulates and remain over the glacier surface during last winter, if it is not discharged in the coming summer, gradually convert from snow to ice. Every year, fresh layers of snow deposit on the glacier upper surface and compress the previous layers. The compression applied by the upper layers, forces the snow below to re-crystallize, forming grains analogous to size and shapes of sugar grains. As time passes, these grains grow large and the air gaps in between two snow grain get smaller, which leads to compaction of the snow grain which results in increase in snow density. Continuing the same process for two years, the snow converts into state called firn. It is an intermediate state between snow and glacier ice which is about half as dense as water. Metamorphism of firn to ice takes place through large number of processes, whose, effect is to increase the grain size, reduce the in between air gaps and thus increase the density of ice to around 0.85gcm³ to 0.90gcm³ (Raina, 2009). With time, these large ice grains convert into crystal shaped structure which becomes highly compressed so that air gaps in between them are very thin. In most of the old glaciers the thickness of ice crystal is in inches. (http:// nsidc.org/cryosphere/glaciers/questions/formed.html).

1.4.2 Glacier Zones

The glacier based on its longitudinal profile is divided into three main component components:

1. Zone of Accumulation (Accumulation Area)
2. Zone of Ablation (Ablation Area)
3. Equilibrium line

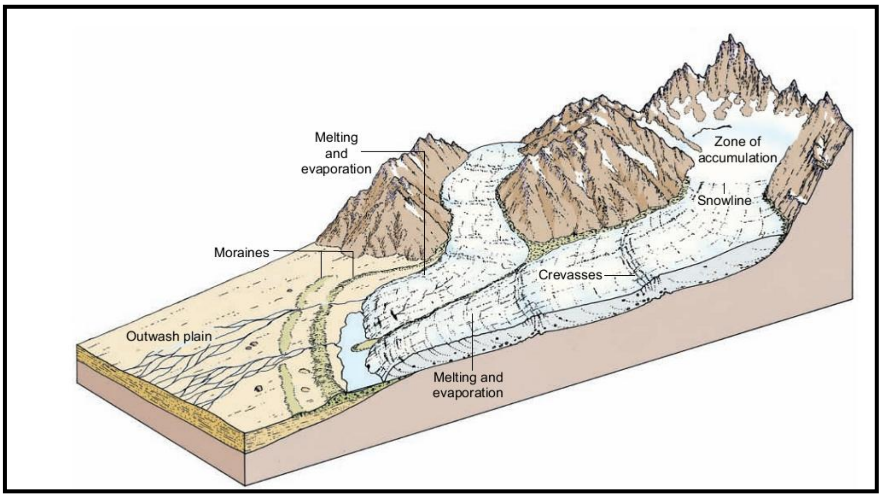


Figure 1.2: *Glacier showing various zones and glacier features.*
(Hamblin &Christiansen, 2003)

1.4.2.1 Zone of Accumulation

The zone over the glacier surface where there occur accumulation of snow or ice compared to previous year is termed as Accumulation Zone, which in turn results in net gain of snow/ice. Accumulation includes all processes that increase the mass of glacier such as snowfall, avalanching, basal freezing, drift snow and internal accumulation. This zone is mostly identified as white in colour in satellite images and generally contains no moraines. (Raina, 2009).

1.4.2.2 Zone of Ablation

Ablation means loss of ice from the surface of glacier mainly by evaporation, melting and calving etc. so, the zone over glacier surface where there occur loss of ice compared to previous year is called Ablation zone of glacier. This area usually contains dirt, debris, moraines and sediments along with melt water, does not easily identifiable in the satellite images. (Raina, 2009)

1.4.2.3 Equilibrium line

The demarcation, separation or line that separators accumulation and ablation zone of glacier is called as Equilibrium line. This line indicates an equilibrium (stable) condition between accumulation and ablation zone. Basically the position of line is governed by mass balance.

1.4.2.4 Snout or terminus position

Snout is the lowermost extreme point in the ablation zone of glacier which actually indicate the health as well as state of glacier i.e. whether glaciers are advancing or retreating. It is first point which marks the melting of ice that accumulates over the high altitude. If the terminus of glacier moves forward due to more accumulation of ice and snow than melting, in such case glacier is said to be advancing. While when glacier melts more than what it accumulates in winter causing terminus to move backwardly then in such cases glacier is said to be retreating. (Raina, 2009)

Zonation of glacier can be done on the basis of surface or faces in microwave remote sensing. Rau.et.al (2000) divides the glacier into dry snow, frozen percolation, wet snow and bare ice also.

1.5 Mass balance

Mass balance is considered as one of the important parameter which assesses the health of glacier. Mass balance in general term is the difference between amounts of accumulation and ablation of the glacier. It gives net change in volume of glacier over a specific period of time. Mass balance is considered to be quantitative entity. Annual mass balance is a hydrological budget which measure difference between accumulation and ablation of glacier during hydrologic year (Knight, 1999). As it depends on accumulation and ablation parameters so mass balance can be positive, negative or may be zero. Glacier showing positive mass balance is found to be growing while negative mass balance indicates glacier is shrinking, and the glacier with zero mass balance shows steady state and no volume change. At any point of glacier, mass balance is usually estimated in kg m^{-2} a^{-1}, but when gets divided with density represented as m of water equivalent (m w.e.) per year. (Kuhn, 2010)

In term of equation, mass balance is represented as sum of accumulation and ablation over time interval of t and t1 which is represented as.

$$b = \int_{t}^{t1} (c + a) dt \qquad (1.1)$$

Where b = mass balance for point,

c = accumulation (due to mainly precipitation) and

a = ablation (defined here negative due to melting) (kuhn, 2010)

1.6 Role of Remote Sensing in Glacier mass balance

Generally point to point measurement of glacier is usually done by traditional glaciological method. Monitoring the glacier mass balance by glaciological technique of observing stakes placed over a glacier's surface is wastage of time and is limited in scope (Dyurgerov, 2002). As all the glaciers are located in the non accessible and remote areas where terrain is very rigid and complex, and weather is so extreme and harsh, making the task of collecting data for mass balance estimation difficult. In such areas, remote sensing proved to be boon. The techniques of satellite remote sensing are particularly proved to be very useful in gathering the information about the cryosphere over a short duration of time. (SAC, 2010) Though Satellite remote sensing is incapable of measuring mass balance directly, but it provides related data with wide coverage at regular interval of time which gives potential for regular and timely monitoring over large glacier cover areas too. The main aspects of the mass balance estimation are the continuous monitoring of glacier boundary (glacier area) and the terminus position. (Kulkarni, 2007).

There is availability of large number of imageries from remote sensing satellites and sensors which are having adequate spatial and temporal resolution, nearly worldwide coverage for monitoring the changes in glacier parameters over large area in less span of time. Several parameters such as mass balance, glacier surface, glacier velocity, glacier zones, surface temperature, reflection, and equilibrium line are possible to be detected by using space borne, terrestrial and air borne. (Racoviteanu *et al*., 2008).

Since last two decades, many of the studies has been done which include snow cover mapping, mass balance measurements, monitoring of snout, meteorological measurement studies, glacier hydrology including discharge measurement, runoff measurement, sediment load and water quality, using multispectral remote sensing as well as ground penetrating radar, but all these studies are restricted over small geographical areas and for short periods. In comparison to large glacier covered area the studied area is statically insignificant. So, in order to keep this in view we should define certain gap areas or problem and should do some work to it.

1.7 Problem definition

Glaciers are one of the nature's landscapes that are directly affected by climate change as it influences the glacial retreat. And glacier retreat is directly dependent on mass balance. But glacier mass balance is best estimated by field work. Mass balance by field based method is threat to life which makes researcher going on such terrain again and again, but instead of field method remote sensing based glacier mass balance estimation is proved to useful. Before estimating glacier mass balance, mapping of glacier is necessary to be done to know about the regions where the glacier's accumulates and where it melts to calculate net budget. So, there is need to find the best and semi automatic techniques for glacier mapping. Since cloud cover is the main problem in optical remote sensing. So, the aid of thermal or microwave remote sensing can be used to know the potential of glacier mapping in addition to optical remote sensing. To process the satellite data and to estimate glacier mass balance by remote sensing there is need to develop an open source image processing tool which helps in mapping and monitoring glacier to understand climatic variability.

1.7.1 Research Questions

- How the microwave, thermal and optical remote sensing techniques are used to improve the glacier feature mapping including the accumulation and ablation areas of the Glaciers?
- How the glacier mass balance can be estimated through different methods using different parameters by Remote Sensing techniques.
- How integration, evaluation and validation of different techniques of GMB can be done in programming environment.

1.7.2 Research Objectives

- To map the accumulation and ablation region of glacier using thermal, microwave and optical remote sensing.
- To estimate and analyze the GMB by different methods using Remote sensing technique and find which techniques is suitable as per my ground data.
- To develop a software or customized GUI tool for the evaluation and validation of different techniques of estimating GMB in GIS environment using open source programming language

1.8 Organization of thesis

This study mainly focuses on the estimation of Glacier mass balance usually by two main methods.

1. AAR method.
2. Geodetic method.

1.8.1 AAR Method

It is well known fact that equilibrium line altitude (ELA) and as well as AAR at the end of melting season is directly related to mass balance of the glacier. (Paterson, 1994). Equilibrium line altitude is that altitude at which accumulation become equal to ablation. Remote sensing approach also contributes in the estimation and approximation of ELA. Another factor on which mass balance depends is AAR. AAR is an acronym for Accumulation Area Ratio. The Accumulation Area ratio is the ratio of the accumulation area to the total area of the glacier (Meier, 1962).

$$\text{AAR} = \frac{\text{ACCUMULATION AREA}}{\text{TOTAL GLACIER AREA}} \quad \text{……………………..….. (1.1)}$$

Based on the studies till now it is found that with the increase in the AAR ratio there occurs changes in annual and net mass balance (Dyurgerov and Meier, 2005). This relationship suggests that change in glacier mass balance can be measured only if the change in the accumulation area of a glacier is estimated. Hence, to estimate the glacier mass balance by AAR, accumulation area needs to be mapped and once accumulation area is determined, AAR ratio can be easily calculated and linear relationship is established between AAR and mass balance.

1.8.2 Geodetic Method

Another important traditional method is geodetic method which is also based on surveying as well as remote sensing approach. It is an indirect method of estimating mass balance in which elevation from older DEMs constructed from historical topographic information are subtracted from the more recent DEMs constructed from Remote sensing imagery such as ASTER, SRTM or SPOT (berthier.*et.al* 2004, 2007).Geodetic method estimates the volume change using difference in the elevation of two different time-series period. This change in volume can further be converted into mass balance when appropriate density depending on various zones can be applied. But density distribution is always is not known so, mass balance can be estimated from elevation change using constant density. (Racoviteanu.*et.al*,2008)

In case of AAR method, there is a need to know about accumulation area and total glacier area, in order to get this parameter there is need to first map the various component of glaciers i.e. accumulation zone from where we get accumulation area and snowline. Various automated techniques has been used to map zone of glacier using optical, thermal and microwave remote sensing, which include NDSI, Band Ratio, NDSTI, Land Surface Temperature and Backscatter Coefficients.

This study also focus on the customization of Mass balance by both geodetic and AAR method in terms of open source image processing tool which will provide an aid to estimate Mass balance. Since very less work on glacier has been done till now, this study can be used to map accumulation and ablation zone and can be able to calculate mass balance on vast areas. To ease somewhat manual work of image processing python is chosen to be one of the programming languages, as this is convenient to work with satellite images and has large use in research area. The framework so selected is PyQt. The overview of the software so developed is discussed in later chapters.

2. LITERATURE REVIEW

2.1 History of Glacier studies

The Himalayas, known to be as “Abode of Snow” attracted many observers since long back as much of the work was written in historical decade of 1840-1850 about “line of perpetual snows” by two eminent writers Jack in 1844 and Humbolt in 1845. The most popular glacier that was visited at that time was Pindari Glacier found in the lower Shiwalik Hill, now in Uttarakhand. In 19th century, cartographers and Geologists took observations of glaciers for map making using triangulation method. In 1862, Godwin Austin, who was a famous renounced topographer , geologist , who explored and surveyed K_2 , also known as Mt. Godwin-Austen, wrote much about upper basin of Indus river and Mustaq Range. One of the first Indian Geologist who wrote about Indian Himalayan glacier was P.N.Bose in 1891, when he visited Kabruand Pandim Glaciers found in Sikkim State. Geological survey of India also stepped to initiated international program, in 1907 to observe and study the fluctuations of the glaciers, which continued for 3 years and ended in 1910. During the time of independence also, people contributed a lot in this field. The first scientist, who examined the role of ice, snow and glaciers in the determination of surface water resources of the Himalaya, was Kanwar sain (1946). Many individual studies had been done by different scientist during 1910 to 1957. In order to observe glaciers another effort was started during 1957-1958 which was considered to be International geophysical year, here, in this program a lot of information had been collected on visting many glaciers regarding history of glacier and glacier fluctuations. Later on decadal program had been started as international programme in 1964-1974 to study many glaciers. (Vohra *et.al*,2010)

In respect of area coverage Wissman (1959), was the first scientist who took estimate of total ice cover and observed that about 17 percent of Himalayas were covered with ice and spreaded over 33,200km^2 area. Later on Qin (1999) estimated and penned down increase in the total ice cover to 35,110km^2. A lot of work had been done in 1800 century at small scale. But with the advance in the technology, required sources and resources and increase in the understanding level, large amount of work has been done in last three decade. (Vohra *et.al*, 2010)

2.2 Global warming - Threat to glaciers

The process that have been increasing since 1976 and threatening the world is the global warming. The important consequences that have been observed during recent decade are the thinning and shrinking of mountain type glaciers (Meier *et al.*, 2003). The possible causes for global warming are anthropogenic activities like increase in the concentration of aerosols and green house gases, along with alteration in land use cover as per IPCC report.

The previous done observations suggested that temperature increases with the increase in elevation which makes plateau and mountain range susceptible to global warming (Beniston *et a*l., 1997). India shows an increasing trend of mean annual temperature from 1903-2003 of around 0.5^{0}C/100yrs. And from 1970 onwards the increase in temperature found to be 0.21^{0}C/10 years. This happens because northern part of country experience significant warming during that period and surge of temperature rise since nineties (Vohra *et al*, 2010).

Even Tibetan plateau experience a sharp rise of temperature 0.3^0C per decade observed during last fifty years even at elevation of 2000 m.s.l. it has been found that warming effect increase with the elevation, Snow accumulation has been decreased (Vohra *et.al*, 2010)

Indian subcontinent also have noted many changes in the distribution pattern of temperature and precipitation over last fifty years revealing that there is a change in frequency of different types of rain events from 1954-2004, which in turn showing that summer monsoon over India is weak. (Dash *et al*., (2009)). The meteorology data obtained during last thirty year over these glacierized region i.e. high altitude regions also showed that there is increase in global warming and decrease in the snowfall in different ranges of North-western Himalayas, showing temperature rise of around 1.6^0C during 1901-2000 (DST, 2012).

Due to above said reason, convergence from global, sub continent and as well as regional data conveying that India has been warming at rapid rate, with north western Himalaya shows the highest rise as per the results deduced from last 3 decades. There is also an alarming threat that warming would lead to reduce snow cover, slope stability, enhanced melting of glaciers, causing increase in sea level, disturb water cycle, affect landscapes, causes increase in sediment load, resulting to cause natural hazards. Taking into account the consequences of global warming on the Indian sub continent there is an urgent need to study glaciers using latest technologies, conduct workshops, carry effective research work and there is also need to build models to make understand different underlying processes and estimate results and solutions to many of the issues and concern through which scientists are confronted.(DST,2012)

2.3 Glacier response to Climate Change

Snout monitoring of glaciers by in-situ or by remote sensing methods has gained much attention and it has found that more than 50 glaciers are monitored till now. It has been found that majority of the glaciers have been retreating (Raina ,2009). Karakoram shows exception in this trend. Studies reveal that there is a decrease in the temperature too over last fifty years. (Hewitt, 2005). Since temporal as well as spatial variations observed in the retreat rate of glaciers and it is found to be less than 5m/year to 50m/year (Raina and Srivastava, 2008). Recent Studies indicates highly accepted fact that change in glacier length also gives the rough estimate of response of glacier to climate change. The advance and retreat of the snout position of the glacier involves dynamics process of ice flow, which in turn is indirect and observable signal of climate change.(DST,2012). Even the relationship between the glacier responses to terminus position with climate change is dependent on the glacier dimension and geometry (Venkatesh et al., 2011). Even the main difficulty arises in understanding the relationship between glacier postion and climate change when debris cover the terminal zone (Scherier et al., 2011).

2.3.1 Factor controlling health of glaciers

The climatic variables of precipitation and temperature influence the glacier formation and survival. Even physical condition of glacier also contributes in accessing the health of glacier. Table2.1 shows the main factors through which glacier state or health can be accessed.

Table 2.1: *Factor affecting the health of glacier*
(Source*: Table from Knight (1999) , hubbard and glasser (2005); Riedel and Burrows(2005); and Singh and Singh (2001))*

Glacier controls	*Conditions favouring glacier development*	*Explanation*
Climatic Conditions		
Precipitation	High and winter dominated	Increase accumulation
Temperature	Low annual mean and Low summer mean	Reduce ablation
Isolation	Low	Reduce ablation
Wind	Low	Reduce removal of snow from glacier surface.
Humidity	High	Increases precipitation and reduces ablation by sublimation.
Physical Condition		
Elevation	Predominantly High	Increased precipitation at high elevation results in increased accumulation Lower temperature at high elevation reduce ablation
Gradient	Low	Low gradient reduces ablation by slowing the transfer of ice from accumulation area to ablation area
Latitude	High	Reduced insulation and air temperature decrease ablation
Continentally	Maritime	Moist air masses increase precipitation and accumulation

Aspect	Poleward and Leeward	Shade reduces ablation and leeward aspect increases drifting accumulation
Accumulation Character	Large area and prone to avalanches	Increases accumulation
Terminal Character	Not terminating in water and cliff	Reduces ablation due to calving or ice avalanches
Landslide/Debris Cover	Frequent landslides and highly debris cover	Thick layers of debris insulate ice reducing ablation
Geothermal Heat	Low	Reduces ablation by decreasing basal melting

2.4 Mass Balance - A Key Indicator

Another important key parameters for assessing the trends of changing climate is the Mass balance of the glaciers,(habserial,1998). Glacier mass balance studies have been considered as important area of study in the estimation of glaciers and icecaps contribution to sea level rise, because they shows real procedure for estimating changes in the ice volume. (UNESCO, 1998) . Long term monitoring of glacier is important because

1. To know the significant relationship between mass balance and climate change.
2. To observe the impact of change in glacier mass balance on the release of water due to melting.
3. Effect of glacier melting on sea rise level.

Glacier have tendency to be in stable state. So, any disturbances due to factors described in the table 2.1 forces the glacier to adjust its position and dimensions. Due to which change is reflected in terms of increasing or decreasing total mass. Figure 2.1 represents complete glacier change processes and linkages depicting the climate change and its impact on glacier.

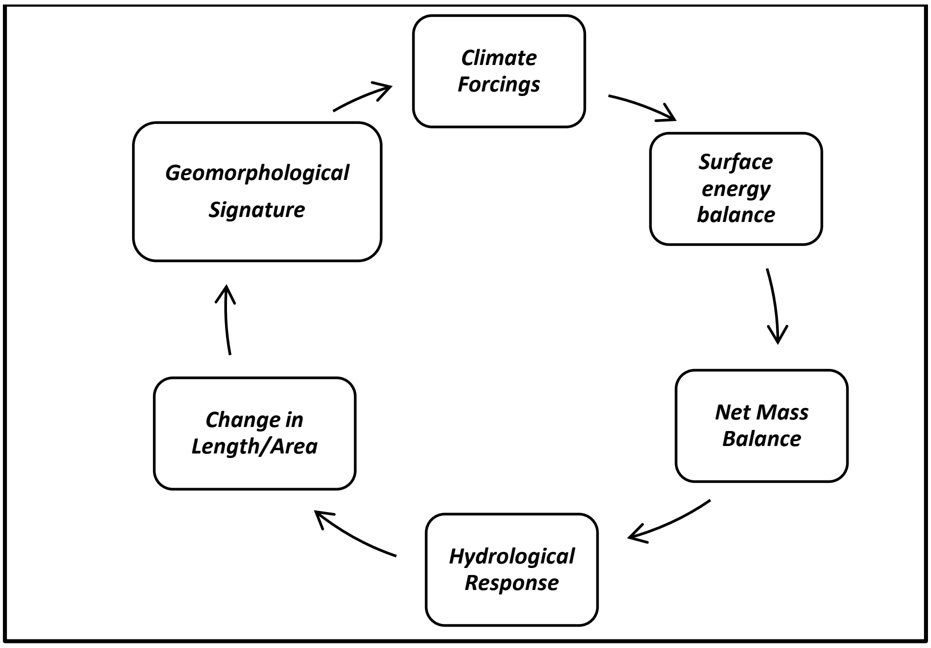


Figure 2.1: *Glacier change Processes and linkages (Fountain et al., 1997)*

Figure 2.1 depicts change in climate leads to cause change in surface energy balance, Glacier Hypsometry and mass balance which in directly affects hydrological regim. Mass budget of glaciers combine the impact of all climatic change of different time periods over spatial scales and it is approved as direct signal of atmospheric conditions. (Haeberli et al.,1998). Mass budget also establishes connection between glacier dynamics and climate in one way and on another way between mountain hydrology and climate.

2.4.1 Glacier Mass Balance Measurements:-

Global climate Observing system (GCOS,2003) defines the basic characteristics of glaciers which are measurable to be Length and Mass balance. Since the important parameters associated with mass balance are AAR (Accumulation area ratio), Equilibrium line altitude (ELA), mass balance gradient and mass turn over and density which all together help to characterize the glacier response to climate change. Among several methods of glacier mass balance estimation, two methods are broadly classified and widely used over last fifty years which are

1. Direct method
2. Indirect method (Paterson,1994)

Direct method involves field measurement needed to determine accumulation and ablation areas of glaciers using stake network, for the calculation of glacier mass balance. This method also uses snow pit to obtain the density of snow and to know its other properties (Dyurgerov and Meier, 1997a). The main methods come under direct method are:

1. Glaciological Method
2. Hydrological method

Indirect Method of estimating mass balance is an independent approach. Usually in this approach mass balance is evaluated using other known parameters. The main methods come under this category are:-

1. Geodetic Method
2. AAR Method

2.4.2 Mathematical concept of mass balance

Generally the annual accumulation (c_a) and annual ablation (a_a) of a year at the beginning (t_1) and end (t_2) of balanced year is given as

$$c_a = \int_{t_1}^{t_2} c \, dt \quad (2.1)$$

$$a_a = \int_{t_1}^{t_2} a \, dt \quad (2.2)$$

Where c = accumulation rate and a = ablation rate.

Annual mass balance is the difference between the annual accumulation and annual ablation.

$$b_a = c_a - a_a \quad (2.3)$$

if t_1 and t_2 are the beginning and ending of winter season, then c_w will be winter accumulation and a_w be the winter ablation and b_w be the winter mass balance. Similarly, if t_1 and t_2 are the beginning and ending of summer season, then c_s will be summer accumulation and a_s be the summer ablation and b_s be the summer mass balance. The value of integral of c_a and a_a w.r.t horizontally projected area (S) of the glacier are called total annual accumulation (C_a) and total annual ablation (A_a).

$$C_a = \iint c_a \, dxdy \quad (2.4)$$

$$A_a = \iint a_a \, dxdy \quad (2.5)$$

The difference between the total annual accumulation and total annual ablation is called the annual net balance (B_n), i.e.

$$B_n = C_a - A_a \quad (2.6)$$

B_n is the annual volume change in glacier. When it get multiplied with the density of ice (taken as 900kg m^{-3}), it takes the units of m^3 w.e (water equivalent). When Bn is averaged over the area of the glacier, the specific (average) net balance can be determined:-

$$b_n = B_n/S \quad (2.7)$$

the annual balance is calculated for fixed period i.e. Hydrological year. And net balance is related to minimum mass the end of each summer. But usually annual balance is calculated at the end of ablation season. Both net as well annual is considered same for hydrological year. (Shiyin *et al*., 2008).

2.4.3 Mass Balance by Glaciological Method

The most widely used technique for monitoring glacier mass balance is Glaciological Method (Singh and Singh, 2001). As this is direct method for measurement of glacier mass balance, so it provides deep information about the processes that control mass balance (Fountain *et al.,* 1997). Mass balance for entire glacier is determined by number of point measurement over glacier surface (Paterson, 1994). At each point, depth of accumulated or ablated snow or ice are determined, and multiplied with snow or ice density to estimate the mass balance at each point (Kaser *et al.,* 2003). To calculate the mass balance over the glacier surface these point values are extrapolated or interpolated (Karpilo, 2009).

Methodology for Glaciological Method: - For the estimation of mass balance, poles are drilled at point locations into surface of glacier. A network of stakes installed in certain pattern which covered the entire glacier. It is dictated logistically that stakes are installed along the centreline of glacier with occasional transverse profiles more or less perpendicular to the longitudinal profile of the glacier. stakes should be distributed over the glacier surface by equal elevation bands , the distance measured should not horizontal but having equal interval elevation of nearly 100m apart (Kaser *et al*., 2003). Once stakes are installed, the location of each stakes is recorded with GPS receiver. Ablation stakes of steel, plastic, aluminium, wood, PVC pipes are used for mass balance investigations (Hubbard and Glasser, 2005, Singh and Singh, 2001). Stakes are installed by drilling hole around 2-4 cm in diameter and 10m in depth (Riedel and Burrows, 2005). The determination of ablation is usually made by measuring the length of exposed stake with tape at start and end of mass balance year. The accumulation is measured by digging pits at selective locations, where snow is accumulated in the past period of investigation (from t_1 to t_2). Snow density is determined using density tube and scale (Kaser *et al.*, 2003). Point mass balance is calculated by multiplying change in stake length measured during end of ablation region with the density so calculated. The mass balance is then extrapolated over accumulation and ablation area to estimate mass balance in different elevation bands. (Karpilo, 2009)

$$b_n = (1/S)\ \{\Sigma(b_{n1}s_1 + b_{n2}s_2 + -- + b_{nj}s_j).\} \ldots\ldots\ldots\ldots\ldots \quad (2.8)$$

where b_n= specific mass balance. b_{n1}, b_{n2}, b_{n3}---b_{nj} are the mass balance calculated at elevation range (j) with area s_j. S is the entire surface area of glacier. (DST, 2012)

Limitation: - Though glaciological method is excellent techniques for accessing glacier mass balance but it also have limitations.

1. It does not account ablation due to calving (Fountain *et. al.*,1997) because Mass balance on calving glaciers needs terminus position and glacier velocity to determine calving rates
2. Glaciological method measures ablation on glacier surface and ignored the sub surfaces changes in the calculations
3. Crevasses do not allow installing stakes in desired pattern.

Other complications are harsh topography, adverse weather conditions, expensive labours and slow rate of data acquisition (Kaser, et.al, 2003).

Interpretation: - This method is considered to be accurate surface as well as ground -based method till up to date as it also provides information about variation of mass balance magnitudes spatially. Monitoring of glacier mass balance by this method provides the deep understanding of hydrologic cycle of the glacier (Karpilo, 2009).

2.4.4 Mass Balance by Hydrological Method

For large basin and complex topography, water balance method also used to determine mass balance, (DST, 2012). The glaciers acts as reservoir with seasonal gains and losses, when hydrology is concerned (SAC, 2010). The water equation used to estimate Mass balance is:

$$w = p + s - e - i - r \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.9)$$

Where, w = water balance

p = annual precipitation

s = snow drift supply from neighbouring basin

e = annual evaporation

i and r are ground and surface runoff at gauge site. (DST, 2012)

But this method is found to difficult to operate, as data measurements of all the parameters needed are not obtained directly. Estimation of glacier mass balance by this method is found to posed complication in storage (DST, 2012), as it is difficult to estimate ground water over such hilly terrain. This method is unreliable as sampling of precipitation, calculation of evaporation as well as run off estimation is difficult to record. Moreover, establishing and maintaining gauging station to get meteorological data i.e for water discharge calculation is expensive and time consuming. (SAC, 2010).

2.4.5 Mass Balance by Geodetic Method

Another practical and possible method for estimating mass balance is Geodetic method. Mass balance by geodetic method is determined by determining the volumetric change in the ice mass over glacier surface from the topographic survey of Surface elevation and extends (Paterson, 1994). Geodetic method of mass balance estimation suggests remote sensing to be an alternative or complementary method to the traditional in-situ glaciological method. There are various methods for calculating Geodetic mass balance including conventional surveying, topographic maps, by aerial or satellite images i.e DEMs (from ASTER, SPOT, Cartosat, ERS data) and lidar surveys. (Karpilo, 2009)

Methodology: - It consists of image acquisition, scanning, referencing, DEM production, and glacier change calculation. The surface elevation change on pixel by pixel basis is calculated by subtracting the two co- registered DEM using GIS software. The method is useful for finding mass balance over long time periods (5-10 years). The elevation data from two different time period provides an effective method of assessing changes in volume of glacier. (Karpilo, 2009). An assumed value of density is multiplied by integrated surface elevation change over the glacier area to determine mass balance or change in volume (Cox and March, 2004).

Timing and frequency:- Glacier Mapping should be conducted in years of minimal snow because anomalous late-season snow can obscure the terminus or margins and make it impossible to accurately determine glacier extent (Riedel and Burrows, 2005)

*Limitations:-*The geodetic method is an effective technique for remotely assessing glacier volume change, but it does have several inherent limitations.

1. It involves high cost geodetic-quality aerial /satellite imagery (Riedel and Burrows, 2005).
2. Assuming "the density of the material gained or lost is equal to the density of ice" (Cox and March, 2004). This assumption may result in overestimating the mass of snow and firn in the accumulation area.

Others errors are poor DEM registration error, ice field with limited relief (Østrem and Haakensen, 1999)

Interpretation:- The geodetic method produces a volume change for the entire glacier, which after some assumptions about density, is converted to mass change. This method provides an important check on the glaciological method and should be used in conjunction with it. The geodetic method does not provide point specific mass balance data, such as annual mass balance up a centreline. The difference in results from the geodetic and glaciological methods is because the geodetic method measures the geometric response to changes in mass input and output, whereas the glaciological method measures the actual input and output. The greatest utility of the geodetic mass balance method is in calculating average balances over long periods of time and in validating the glaciological cumulative mass balance (Singh and Singh, 2001).

In French alps Studies were conducted which shows better correlation between mass balance derived from glaciological and geodetic method (Rabatel et.al., 2005). One more study Hagg et al., (2004) make comparison of mass balance derived from glaciological , hydrological and geodetic method for glacier named as Tuyuksu in central Asia and found a good agreement between glaciological field measurement(-16.8m w. eq.) and geodetic method (-12.6 m w.eq.).

2.4.6 Mass Balance by AAR Method

Another alternative satellite based glacier mass balance is AAR method. Mass balances are derived from two parameters AAR and ELA. The AAR/ELA is developed by Kulkarni (1992a) and well established fact is that ELA at the end of ablation season is directly proportional to mass balance (Paterson, 1994). This method is relying on the following assumptions:-

1. Under steady state conditions, accumulation area of glacier (area above ELA) occupies fixed percent to the total area.

2. The elevation of snowline altitude at the end of ablation period usually coincides with equilibrium line altitude (Paterson, 1994).

The approximate value of ELA is usually evaluated using band ratio which visually differentiates both accumulations as well as ablation area. The debris covered or dirty ice is less reflective and has less albedo (0.15-0.2) while fresh snow appear more reflective that is found in accumulation zone (=0.85). The difference in reflectivity of accumulation and ablation is used to delineate the transition line, and determine the respective areas. DEM is used to extract ELA line. The yearly AAR is easily determined from ELA and accumulation area delineated from glacier using satellite image. Area above the ELA comes in accumulation zone while below ELA comes under ablation zone. The value for AAR also varies from one glacier to another as mass balance changes. This works as regional models also. ELA/AAR method focuses on the relationship between mass balance and AAR. The relationship so establishes are found to be valid for a single glacier or glacier for same climatic zone (Kulkarni, 1992a). The relationship is as under:-

$$B_n = a * AAR + b \qquad (2.10)$$

Bn = specific mass balance in water equivalent (m w.e.) and AAR = Accumulation area ratio

The value of AAR where mass balance found to be zero is known as AAR^0 (steady AAR). AAR method is applied using Landsat imagery in Western Himalayas for different years on several glaciers found that AAR^0 value for western glacier is around 0.44 (Kulkarni,1992a) whereas for alpine glacier, it comes out to be 0.67 (Paterson,1994) and for tropical glaciers AAR^0 found to be 0.82 (Meier and Post,1962)

The mass balance relationship with AAR also depicted in figure 2.2 for Shaune Garang and Gor Garand glaciers shows a good correlation of 0.80 validating the relationship between two parameters (Kulkani et al., 2004)

Limitations:-

1. It is approximation of glacier mass balance.
2. Actual relationship of mass balance and AAR differ from glacier to glacier. At higher elevation and latitude the process of or effect of internal freezing of meltwater at the base of snowpack become important and due to this water get frozen and mistakenly consider as as snow , firn or ice leading in difficulty in plotting ELA
3. Timing and availability of data at the end of ablation season (Karpilo, 2009).

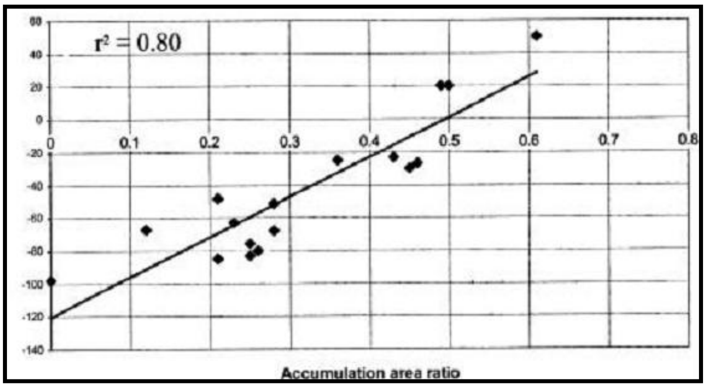


Figure 2.2: *Relationship between AAR and Massbalance (Kulkarni et.al,2004)*

Interpretation: ELA and AAR does not provide good estimate of change in mass balance unless specific information about a site is available. If the mass balance measurements for a specific site are available for long time then relationship between the two parameters can be established and in situ field measurement can be terminated. However the glacier cannot significantly change its geometry otherwise relation between variable need to be change (Karpilo, 2009).

2.5 Review on Global Mass balance

World Glacial Monitoring Service (WGMS) is an official agency of International Association of Cryospheric sciences, earlier called as international commission of snow and ice maintain database of mass balance of glaciers. This organization is publishing records for glacier mass balance since 1967 in the volume of *Fluctuations of Glaciers* after every 5 years. Review of nearly 10-15 glaciers since 1991 has been published in *Glacier Mass Bulletin.* Dyurgerov (2002) and Dyurgerov and Meier (2005) has done detailed analysis of global In mass balance of the glacier data for period 1946-1998. They deduced that:-

- In between 1961-1998, the average mass balance found globally is -212mm w.e.units, showing -93mm for 1961-976 and -294 mm for 1977-1998
- 1977-1998, the value of b_w increased by 7% whereas b_s increased by 9% as compared to 1961-1976.
- ELA also has been increased by 200m.
- AAR decreased from about 60% in 1968 to 50% in1998.
- The vertical mass balance gradient shows increase in ablation rate below ELA and increase in accumulation rate above ELA.

2.6 Review on glacier Mass balance over Himalayan Region

Kulkarni et.al., (2004) established relationship between AAR and mass balance for 19 Glaciers in Baspa region using satellite IRS data. The study depicted that remote sensing is only the practical approach of estimating mass balance over difficult and hazardous terrain. So, far about 13 glaciers has been studied using glaciological method, most of the measurement is done during 1974-1990. The time period over glacier study varies from 2 to 10 years. The longest time data is available for Shaune Gorang glacier. Presently constant monitoring of four glacier have been done which include Chhota Shigri (JNU), Dokraini and Chaurabari (by WIHG), Hamtah (GSI). The given below table 2.2 shows the mass balance of several glaciers calculated over different regions over different period of time in Himalayan Region.

Table 2.2: *Mass balance Estimation of Selective Indian Glaciers for different time periods (**Source**: DST (2012)).*

Name of the glacier	***State***	***Period***	***Mean Annual Specific M.B (b_n)***	***Agency***	***Reference***
Rulung	J&K, Ladakh	1980-83	-0.11	GSI	GSI(2001)
Neh Nar	J&K	1978-84	-0.52	GSI	GSI(2001)
Gara	HP	1975-82	-0.31	GSI	GSI(2001)
Gor Garang	HP	1977-85	-0.43	GSI	GSI(2001)
Shaune Garang	HP	1982-91	-0.42	GSI	GSI(2001)
Chhota Shigri	HP	1987-89 2003-2006	-0.16 -0.98	WIHG JNU/IRD, Fr	Dobhal et al.,1995/ Wagnon et al., 2007
Hamtah	HP	2001-06	-1.6	GSI	WGMS(2008)
Naradu	HP	2001-03	-0.4	Jammu Uni.	Koul and Ganjoo,2009.
Dunagiri	Uttarakhand	1985-90	-1.04	GSI	GSI(2001)
Tipra Bank	Uttarakhand	1982-85,88	-0.41	GSI	GSI(2001)
Dokriani	Uttarakhand	1993-95 1998-2000	-0.32	WIHG	Dobhal et al.,2008
Changme Khangpu	Sikkim	1980-83	-0.34	GSI	GSI(2001)

For period of 1999-2004, the overall mass balance is -0.7 to -0.85 m/a w.e. as per the density adopted. Glacier Mass balance for Bara Shigri and Chhota Shigri are -1.31 m/a w.e. and -1.12m/a w.e. respectively. (DST, 2012)

Mass balance estimation in 2000-2001 and 2001-2002 in the Baspa region (H.P) are -0.9m/a w.e. and -0.78m/a w.e. (Kulkarni et al., 2004) which uses the AAR method using Remote sensing data. The other glaciers i.e Chorabari (UK) Raina,(2009) also give average value (2003-2007) is -0.75m/a w.e. Mass balance available in Dasuopu Glacier in Tibet shown a negative mass balance of -1.0 m/a w.e. during 1996 (Thompson et,al, 2000).

Dobhal et al., (2004) used SOI toposheet of 1962 and large scale maps on (1:10,000) scale calculated the changes in glacierized area and ice volume on Dokarani glacier.(DST,2012)

2.7 Literature Review on Study area

The monitoring of Chhota Shigri glacier began during 1986 to 1989 was organized by WIHG and DST. During the expedition of glacier, morphology, meteorological parameters, mass balance, and glacier dynamics have been surveyed Topographic map of 1:10,000 map of Chhota Shigri was prepared by SOI. The snout treat has been estimated to be 53.5myr^{-1} between1988 and 2003. (Kulkarni,2007) which concludes that results from remote sensing data is matched with field observations.

Mass balance studies for 8 years has been done which indicate that glacier experience overall negative mass balance , the cumulative mass balance found to be for 2002-2010 is -5.37m/a w.e. A slight positive mass balance value of 0.1m/a w.e. is measured for Chhota Shigri for 2004-2005. The earlier mass balance during 1987-1989 will be around -0.16m/a w.e. During 1987-1989 the ELA varies between 4650m to 4700m with AAR variation of 65% to 73%. Whereas, as per the studies done ELA varies between 4855m amsl to 5185m amsl with value of AAR varies between 29% to 74%. (Ramananthan, 2011)

2.8 Glacier Monitoring

The most prominent application of multispectral remote sensing in glaciology field is the mapping of glacier extent. Since the number of sensors that can be used to map and monitor glacier is more and still increasing. But based on availability, spatial resolution and spectral resolution only few sensors can be used which are Landsat, SPOT, ASTER, and IRS. Since the orthorectification of the nine bands of ASTER and SPOT, which require high accuracy, are very tedious. So, Landsat and IRS being single band chosen to be suitable to work on glacier mapping and monitoring.(Pellika and Rees, 2010).

Snow shows higher reflectance in the visible region of EM spectrum and less reflectance in the middle and shortwave infrared regions (Pellika and Rees, 2010). Fresh snow shows higher reflectance in visible and near- infrared region. The partially compacted snow i.e Firn shows 20-30% less reflectance than snow, while ice in glacier region shows very high reflectance in blue, green with wavelength varying in the respective range (400-500nm), (500-600nm) and zero reflectance in red regions with (600-700nm). Debris cover in glaciers will reduce reflectance (Pellika and Rees, 2010). Similarly albedo is also one of the characteristic that make clear differentiation between ice and snow. Snow has high albedo

(0.8 – 0.97) while dirty ice has only low albedo (0.15-0.25). Snow and ice reflectance are main characteristic that are measured using remote sensing techniques and assists in delineating glacier boundaries and classifying various Cryospheric surface types (Pellika and Rees, 2010). It has been found that different bands of Landsat sensors are used to monitor different parameters and component of glaciers .Table 2.3 summarized different bands of Landsat proved useful in glacier mapping.

Table 2.3: Bands of Landsat showing application in glacier monitoring and mapping (Source: Pellika and Rees, 2010)

TM band	*Field of application*
1 (blue)	Snow and ice discrimination in cast shadow, mapping of glacier lakes, NDSTI
2 (green)	One part of the NDSI(snow), also Snow/ice discrimination in cast shadows
3 (red)	One part of the band ratio, also for NDVI(vegetation)
4(NIR)	One part of the band ratio, for NDVI(vegetation) and NDWI(water)
5(SWIR)	Mandatory band for automated classification(ratio, NDSI)
6(TIR)	Alternate for TM5 in case of thin volcanic ash layer
7(SWIR)	Similar to band 5 but very noisy in shadow
PAN	Manual delineation, debris-cover on glaciers

Similar feature found in IRS satellite because bands are same. Glacier zones are mapped by various techniques:-Glacier studies are first carried out with Landsat, so at the beginning FCC from multispectral images was used to delineate accumulation and ablation area of glacier or in other words to differentiate ice from glaciers. Later on, with the introduction of TM, manual delineation of glacier on FCC image for MSS data is done in combination of TM. Segmentation of ratio images with threshold and at last is the supervised classification to classify zones.

FCC: FCC method to delineate the glacier zones was first used by Ostream (1975). On applying technique on Josttedalbreen icecap, FCCs were generated to distinguish accumulation and ablation zone. A technique has developed (MSS 5 * MSS 6) for automatic glacier classification (in ice, snow, other) for a small region in Tyrol and revealed quite good results.

The second method was applied especially to Landsat MSS data and the derived glacier outlines were afterwards combined with a false color composite (FCC) was manual digitization. The images derived glacier length after co registration and showed good result in comparison with ground measurements (Hall et al., 1992).but it is time consuming method for manual digitization of large number of glaciers as it solve problems of debris on glacier tongue.

The third method for the glacier mapping is classification. With the use of training samples selected on the Landsat MSS and TM satellite images Gratton et al.,(1990) used GIS to do maximum likelihood classification resulting high accuracy for most of the classes(snow, ice, vegetation, bare rock) and though debris need to get digitized using visual inspection. It is found that the accuracy level from the second method has been increased from 0.74 to 0.87 in case of TM and 0.61 to 0.85 (with MSS). The development of technique of segmentation of images opened a new world in the field of mapping and monitoring of glaciers and it is concluded that algorithms of TM 3 / TM 5 ratio images give better result in shadow region than TM4/TM5, whereas the latter show good result in the glacier mapping. Segmentation threshold of *R*(TM 4) / *R*(TM 5) > 1.0 is used to extract the perimeter of Barnes Ice-caps. (Jacobs et al. (1997))

3. STUDY AREA

3.1 Chhota Shigri

The Glaciers of Western Himalayas contribute a large fraction of area to the total area of the glaciers found worldwide. Chhota Shigri glacier is one of long term monitored glacier. Most of the Scientists and Organizations have done lot of work on this glacier. In 2002 the Commission of Cryospheric science, previously named as the International Commission of Snow and Ice selected this glacier as one of the benchmarks in whole Hindu-Kush-Himalayas (Kumar et al. 2007), where in the same year training program was organized by HKH-UNESCO-FRIEND on this glacier with participation of other researchers from India, Bhutan and Nepal (Wagnon et al., 2007). The reason for making Chhota Shigri as bench mark glacier by ICSI because of following characteristics that this glacier has well defined catchment, simple geometry, known accumulation area, relatively debris free, smooth surface , neither too small nor too big and easily accessible (Ramanathan et.al., 2011). This glacier has been continuously observed, monitored and studied by glaciologists and researchers of different countries. A joint team of Indian and French researchers made effort to measure the continuous field mass balance measurement from 2002-2007 (wagnon et a.l, 2007).

3.2 Geographical Location

Chhota Shigri glacier is a valley type glacier which extends over 32.19° - 32.28°N latitude and 77.48° - 77.55°E longitude. The glacier is located in the upper basin of Chandra River basin in Lahual and Spiti valley of Himachal Pradesh in Western Himalayas, contributing to the Chenab River, which is considered to be one of the tributaries of the Indus river basin. This Chenab river flows through Jammu and Kashmir, passes Punjab and then goes into Pakistan. The length of the glacier is about 9 km from snout to Sara Umga Pass which covers mainly with ice, debris, snow and debris covered with ice. The glacier covers around 15.0 to 15.5 km^2 with height varying from approx 4050m – 6263m (m.a.s.l) (Sangewar et al., 2009, Wagnon et al., 2007). The orientation of main glacier is in north direction, but it shows variation in orientation of accumulation area and normally has north-south in its ablation area. (Wagnon et al., 2007). The Chhota Shigri glacier is also sustained by tributary glaciers which normally originate from peak of average altitude of 6000m (a.m.s.l) from the east and at around 5500m amsl from west respectively. The location map of Chhota Shigri is as under figure 3.1. On the east side of this glacier, there situated largest glacier of Himachal Pradesh i.e. Bara Shigri, which is about 28 km long and around 131 km^2 in aerial extent (Dutt, 1961; Berthier et al., 2007; Sangewar and Shukla, 2009).

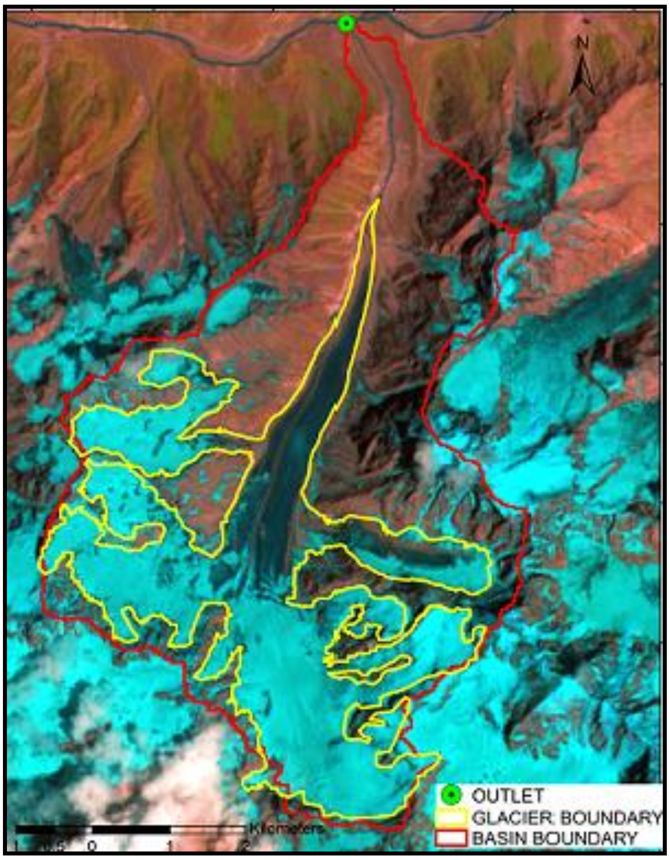


Figure 3.1: *The Chhota Shigri Glacier in Lahual and Spiti district of Himachal Pradesh as seen in the LiSS-III image of IRS P-6 dated 27 July 2012*

3.3 Glacier Morphology

Chhota Shigri is a compound valley glacier. Its drainage consists of four tributary glaciers and other small attached glaciers with total area of 34.7 km^2. (Wagnon et al., 2007). The slope of the glacier is about 0°- 10° in lower region and 20° - 60° at higher elevation region (Kumar and Dhobal, 1997). The snout of the glacier is well defined and easily identifiable and gives rise to only one proglacial stream. The glacier at its lower most regions consists of big boulders, rocks, debris and cobblers. The snout of the glacier is found to be around 3km from the main stream. Different types of landforms are usually found in the glacier like crevasses, moulin, and lateral moraines, till deposits, water stream and conical and pyramidal peaks. Figure 3.2 and figure 3.3 depicts the field photos taken on 21 and 22 September 2012, which shows crevasses' and glacier feature "Moulin" in Lower Ablation Zone respectively.

***Figure 3.2**: Snow covered Crevasses in Lower Ablation Zone*

***Figure 3.3:** Glacier feature "Moulin" in Lower Ablation Zone*

***Figure 3.4:** Photograph of Snout of Chhota Shigri Glacier taken on dated 23rd Sep, 2012*

From the satellite images and field experience by various scientists, various morphological zones are identified like accumulation zones, snout and ablation zones etc. The accumulation zone is mainly surrounded by peaked mountains forming cirque. The glacier is flanged at higher elevation covers large area and become narrower at lower elevation. The ablation zone of glacier is mainly covered by debris and surface moraines. Snout of the glacier is surrounded by moraines. From the snout to equilibrium line the glacier is entirely covered by ground moraines and rocks and debris.

There are mainly two principle types moraines present in the main truck of glacier and these are:-

1. Lateral moraine

2. Medial moraine

Lateral Moraines

Along the sides of glacier, there develop two lateral moraines which generally contains till deposits. When the ice moves it carries rock as well as debris along the margin from abrasion and form a marginal zone of dirty ice. Due to the melting of the dirty ice, below the snow line debris concentrates linearly along the side of the glacier that is called a lateral moraine. In Chhota Shigri glacier, one of the moraines on the eastern side is 4.5km long at an elevation starting from 4750m and finally reaches up to 4,100m. While the other is on western side and is about 4.8km which originates from 4800m and extends to 4200m in a narrow ridge along north-south direction (Dobhal et al., 1995).

Medial Moraine

Medial moraine generally came into existence on the merging of lateral moraine of two glaciers. In case of compound glaciers, the tributary glacier, when merges to the main trunk of glacier leading lateral moraine of tributary glacier to merge and form medial moraines which further move down and form ridge at the centre of the main trunk of glaciers. The medial moraine like lateral moraine also starts from upper part of glacier. As per Shruti (2008), the medial moraine in Chhota Shigri extend from approximately 4850m to 4575m which overall covers around 3.5 km and are usually represented as uplifted surface.(wagnon,2007).

During the field Visit GCP points has been collected for one base at Chhota Dhara and four rover point at JNU base camp, lower ablation area , At snout, Lower ablation area with snow. The Skipro is used for the processing and correcting the GCP points. DGPS GCP after procession is represented in table 3.1, while the location of these points on satellite image is shown in Figure 3.5

Table 3.1: *Location of GCP points collected after processing through SkiPro*

GCP POINT NAME	***LATITUDE***	***LONGITUDE***	***ELEVATION***
BASE (CHHOTA DHARA)	32.29356	77.5222	3755.067
JNU CAMP	32.28606	77.53104	3837.28
LOWER ABLATION	32.27054	77.53041	4154.641
SNOUT	32.26571	77.52785	4211.029
LOWER ABLATION WITH SNOW	32.25894	77.52768	4355.389

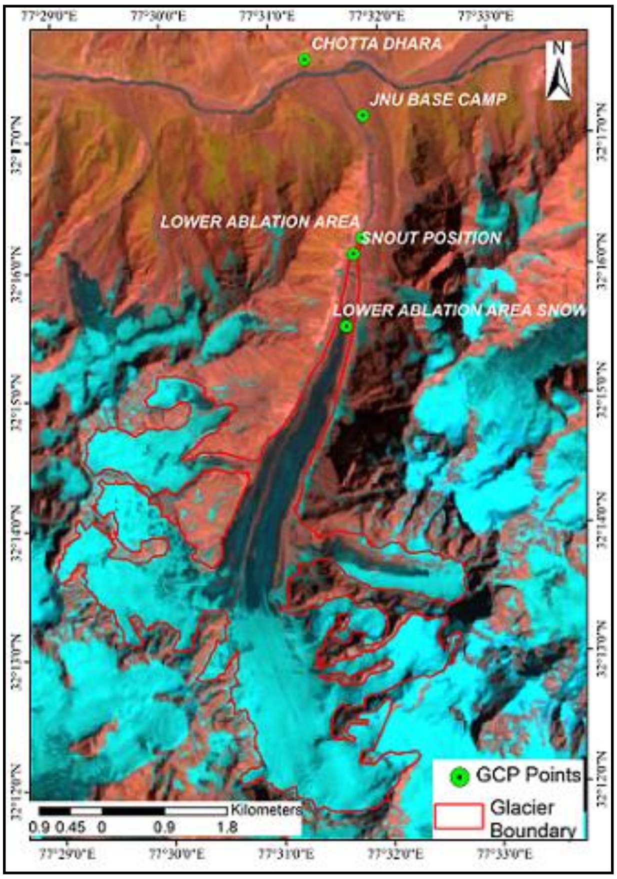


Figure 3.5: *Satellite image showing Chhota Shigri with collected GCP Points collected during Field visit*

3.4 Climate Scenarios

Chhota Shigri is one of glacier which is located in climatically important part of Himalayas. This region comes under monsoon arid-transition zone which encounters monsoon in summer and disturbances from west in winter (Ramanathan, 2011). The annual precipitation of Chhota Shigri glacier is in the range of 150-200cm in the form of snow (Nijampurkar and Rao, 1992). This area experience most of the precipitation in summer season due to Asian monsoon in the month of July to September and in lesser amount in winter i.e. from January to April due to mid- latitude westerlies. The meteorological data collected at the surface of glacier as well as base camp for the year of 1986, 1987, 1989, 2003, and 2009 is highlighted in table 3.2 and table 3.3.

Table 3.2: *Obseravation at glacier surface (Rizvi, 1987; IMD, 1987; Apte et al., 1988;kulandaivelu et al., 1989; Upadhyay et al., 1989; Sharma, 2007, JNU-IFCPAR, 2009)*

	1986 (4700m)	***1987 (4500m)***	***1987 (4500m)***	***1989 (4600m)***	***2003 (4343m)***	***2009 (4920m)***
	18Aug – 8 Sep	***Jul 18 – Aug 17***	***Aug 2 – Sept 5***	***Aug 17- Sept 11***	***Oct 2- 8***	***18Aug - 10 Oct***
Highest max Temp (°C)	10.5	11	8.1	7.5	9.64	11.85
Lowest min Temp. (°C)	-4.5	-1.3	-5.2	-1.6	-6.22	-13.64
Mean Temp (°C)	3.4		3.2	3.2	0.7	-0.76
Highest max R.H (%)	99	97	91	93	78.5	98.7
Lowest min R.H (%)	12	51	60	73	10.1	7.1
Mean R.H (%)	71	78	78	82	70	63

Table 3.3: *Observation near base camp*
(Rizvi, 1987; Apte et al., 1988; Kulandaivelu et al., 1989, Upadhyay et al., 1989)

	1986 (3816m)	***1987 (3816m)***	***1988 (3870m)***	***1989 (3870m)***
Highest max Temp (°C)	18	19.6	19.4	17
Lowest min Temp. (°C)	4.5	3.4	3.2	0.1
Range	13.5	16.2	16.1	16.9
Mean Temp (°C)	10.4	12.8	11.5	9.2
Highest max R.H (%)	98	88	91	92
Lowest min R.H (%)	23	32	40	34
Range	75	56	51	58
Mean R.H (%)	70	47		59

3.5 Meteorological Parameters

Glaciologists have done a lot of research of Chhota Shigri glaciers. It has been concluded that the annual temperature variation near snout or terminus is around 15 °C to 20°C and near snow line is around 7 °C to -15 °C. It has been observed that during the ablation period i.e. during July and August, the temperature lies in the range between 4° C to 20° C. Temperature ranged between -5.2 °C to 10.5°C at ELA on the glacier during July- September and around maximum 16 °C and minimum of 4 °C was recorded near snout (Dhobal et al, 1995). The albedo values for different type of snow have been measured and are given in the table 3.4 (Upadhyay et.al, 1989).

Table 3.4: *Albedo of various objects by (Upadhyay et.al, 1989)*

Glacier Objects	***Albedo (%)***
Fresh Snow	70-90
Dry Snow	56-86
Snow(1-3days) old	49
Old dry snow	44
Old wet snow	35
Ice(black)	16
Rock(surface)	28

4. DATA USED

4.1 DATASETS USED

Since, the change in glacier is not homogenous in space and time. To study such changes there is need to generate a time series of glacier by collecting satellite scenes from different sensors passing over this region in the month of August. The main criteria needed to be fulfilled while selecting the scenes under study is that the images should be cloud free and the area should not come under shadow. Various sensors having medium and high resolution can be chosen like Landsat TM5, Landsat ETM, and Indian Remote Sensing Satellite (IRS) to map and monitor the different component of glaciers. Components of mass balance are not directly measured from space borne satellite but the parameters used to evaluate mass balance can be estimated. Mainly four different datasets needed to carry out the necessary study.

4.1.1 Optical Datasets

Optical sensors usually detect reflected radiation from earth surface's in the range of 0.4µm – 2.5µm. This wavelength corresponds to the visible (VIS) and near infrared (NIR) bands of electromagnetic spectrum which is known as reflective part of spectrum. In total 8 scenes are selected for our study from Satellite Landsat, Resourcesat-1, IRS-1C, IRS-1D. Two images of the study area as 17 August 1997 and 5 September 1998 were taken from sensor LISS-III under IRS-1C and one scene of 20 August 2008 from sensor LISS-III under IRS-1D. From Landsat TM, two scenes have been selected 13 August 2009 and 16 August 2010. From Landsat ETM+, only one scene for 25August 2000 have selected. These scenes are downloaded free from the NASA website. From IRS –P6 (Resourcesat-1) two scenes of 23 August 2005 and 18 August 2006 under LISS-III have been taken for study. All the information about data and source is summarized in table 4.1.

Table 4.1*: Information about data used*

DATE	*SENSOR*	*SATELLITE*	*DATA SOURCE*
17 August 1997	LISS III	IRS-1C	NRSC
05September 1998	LISS III	IRS-1C	NRSC
28 August 2000	ETM	LANDSAT_7	USGS
23 August 2005	LISS-III	IRS-P6	NRSC
26 August 2006	LISS-III	IRS-1D	NRSC

20 August 2008	LISS-III	IRS-1D	NRSC
13 August 2009	TM	LANDSAT_5	USGS
16 August 2010	TM	LANDSAT _5	USGS

4.1.2 Sensor Characteristics

IRS-1C, IRS-1D, IRS-P6 has Linear Self Scanning Sensor (LISS-III), multispectral sensor having 4 bands that provide spatial resolution of 23.5 metres. While LANDSAT 5 has seven band ,Out of which 6 bands 1-5,7 bands works in wavelength range of optical region with spatial resolution of 30 m and LANDSAT 7 has eight bands consisting of 6 optical multispectral bands (band 1-5,7) having 30m spatial resolution and band 8 is a Panchromatic with 15 m spatial resolution.

In Landsat-5 ,TM sensor (Thematic Mapper) corresponds to band 6 has resolution of 120 m ranging in between wavelength of 10.4 µm -12.5 µm which senses thermal infrared radiation. While ETM+ sensor (Enhanced Thematic Mapper) has band 6_1 and band 6_2 corresponds to wavelength (10.4 µm -12.5 µm) with spatial resolution of 60 m.

The satellite images obtained from the Landsat satellite all geocoded. But in case of IRS, all the images were not geocoded. Ancillary information about satellite images has been summarized in table 4.2.

4.2 Digital Elevation Models

4.2.1 ASTER (GDEM)

ASTER DEM is a joint product developed and made available to the public by Ministry of Economy, Trade and Industry (METI) of Japan and the United States National Aeronautics and Space Administration (NASA). It is generated from data collected from the Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER), a space-borne earth observing optical instrument. The ASTER GDEM is only DEM that covers the entire land surface of Earth at high resolution. The Aster GDEM is available at no charge at worldwide from NASA’s land processes Distributed Active Archive Centre(LPDAAC). It has an along track stereoscopic capability using its near infrared spectral band and its nadir viewing and backward viewing telescopes to acquire stereo image data with a base –to- height ratio of 0.6. Aster GDEM is in GeoTiff format with geographic lat/long coordinates and a 1 arc-second (30 m) grid of elevation postings. It is referenced to the WGS84 geoid. It is used to delineate Chandra valley basin and to calculate mass balance also.

4.2.2 Base map

Base map or topographic map is used to digitise the contour interval of 40 m, to get elevation information.

4.2.3 SRTM DEM

Shuttle Radar Topographic Mission (SRTM) is used to calculate Mass balance from geodetic method. It is downloaded freely from USGS site. The spatial resolution of SRTM is usually 3 arcs second which while processing gets resampled into 1 arc second. It is of Feb 2002.

Table 4.2: *The ancillary information present in the header files of the data used, which help in the conversion from radiance at sensor to reflectance (Chander et.al., 2009, Pandya & others, 2002, Kumar et al 2012)*

Date of Pass	*Satellite and Sensor*	*Bands and wavelength in (micrometers)*	*Row/Path*	*SpatialResolution (in mtrs)*
17 Aug 1997 5 Sept 1998	IRS-1C (LISS-III)	B2 (green) - 0.52-0.59 B3 (Red)- 0.62-0.68 B4 (NIR)- 0.77-0.86 B5(SWIR) – 1.55- 1.70	95/48	23.5
28Aug 2000	LANDSAT (ETM)	B1(blue) 0.45-0.51 B2(green) 0.51-0.60 B3(red)-0.61-0.69 B4(VNIR)-0.76-0.90 B5 (SWIR) 1.55-1.75 B6 (TIR) 10.40-12.5 B7(SWIR) 2.09-2.35 B8(PAN) 0.52-0.90	147/38	30
23 Aug 2005	IRS-P6 LISS-III	B2 (green) - 0.52-0.59 B3 (Red)- 0.62-0.68 B4 (NIR)- 0.77-0.86 B5(SWIR) – 1.55- 1.70	95/48	23.5
26 Aug 2006	IRS-1D LISS-III	B2 (green) - 0.52-0.59 B3 (Red)- 0.62-0.68 B4 (NIR)- 0.77-0.86	95/48	

20 Aug 2008		B5(SWIR) – 1.55- 1.70		23.5
13 Aug 2009 16 Aug 2010	LANDSAT TM	B1(blue) 0.45-0.51 B2(green) 0.51-0.60 B3(red)-0.61-0.69 B4(VNIR)-0.76-0.90 B5 (SWIR) 1.55-1.75 B6 (TIR) 10.40-12.5 B7(SWIR) 2.09-2.35	147/38	30

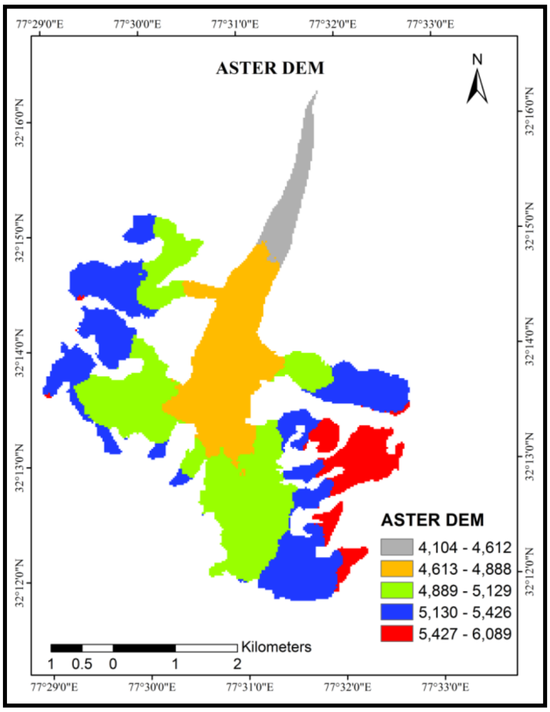


Figure 4.1: *ASTER DEM showing Elevation of Chhota Shigri Glacier*

4.3 RISAT-1

RISAT is acronym for RADAR IMAGING SATELLITE, is a new remote sensing satellite, developed by Indian space research organisation as its first satellite using an active RADAR sensor system. RISAT - 1 carries a multimode C- band (5.35 GHz) Synthetic Aperture Radar (SAR) as the payload. The choice of C- band frequency of operation and RISAT - 1 SAR capability of imaging in HH,VV,HV,VH and circular polarizations will ensure wide applicability in the thrust areas like flood mapping, Agriculture & crop monitoring, generic Vegetation, Forestry, Soil Moisture, Geology, and Sea Ice and Coastal processes etc. http://www.nrsc.gov.in/assets/pdf/brochures/risatnew.pdf. Since it launched in April 2012, so, we got scene for August area.

Table 4.3: *Information of RISAT-1 Scene used for Study*

Date	***Mode***	***Polarisation***	***Node***	***Incidence angle***	***Image format***	***Processing level***
8 Aug,2012	MRS	HH,HV	Descending	37.272	CEOS	SLC

4.4 Software used

ERDAS Imagine, ArcGIS, ENVI, GEOHEC –HMS, SKIPRO, ISRO CEOS READER
Supportive Software: - Microsoft office, Window7.
Programming language: - Python Version 2.7
Framework:- PyQt 4.6.8
Python Libraries: Numpy, GDAL1.9.3, GDAL Utilities, MatplotLib, PIL, Scipy

5. METHODOLOGY

The following steps need to be carried out to do required study.

- Delineation of Chandra Valley Watershed boundary using Arc Hydro Tools and Geo-Hec-HMS by ASTER DEM.
- Scanning , Georeferencing and Mosaicing of Base Map to digitise Glacier boundary
- Geometric correction i.e. Image registration of all the IRS imageries with Landsat Geocoded image in WGS84, UTM Zone no 43. Radiometric Correction:-Conversion of Radiance and Reflectance for all the images.
- Calculation of a various indices i.e. NDSI, NDSTI, Band ratio to differentiate snow and non snow area and shadow.
- To map zones of glacier using thermal data, Single channel algorithm has been applied which use additional parameters like water vapour content and emissivity.
- Processing of Risat 1 data and applying required threshold to do zonation of glacier using backscattering coefficient.
- Application of appropriate threshold to map accumulation and ablation zones of glaciers and calculation of Accumulation area.
- Establishing the linear relationship between Mass balance and Area accumulation Ratio.
- Calculation of AAR for each satellite image and estimation of annual mass balance.
- Digitization of contours at an interval of 40 meters from Base map to form DEM.
- Calculation of mass balance using geodetic method using Base map DEM and SRTM DEM.
- Development of Graphical User Interface to calculate Mass balance.

The overall methodology of the above study done has been given in flowchart as figure 5.2.

5.1 Water Delineation and Boundary Digitization

ASTER DEM is used to delineate basin boundary using flow accumulation, flow direction, drainage map and pour point or sink point. The approximate outlet point has been taken from Google earth due to which we get Chandra valley watershed basin.

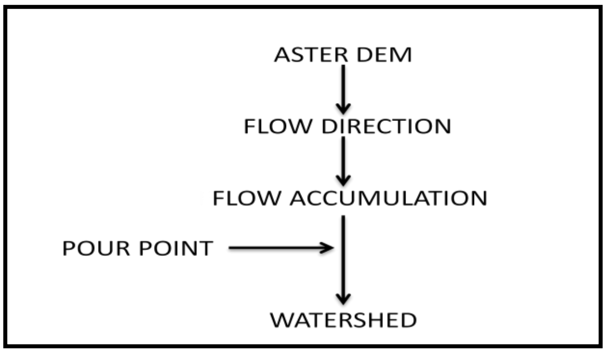


Figure 5.1: *Flow chart for the Watershed delineation from ASTER DEM*

Base map of Chhota Shigri is Georeferenced, Mosaiced and used as reference to extract the glacier boundary

5.2 Satellite Image Processing

5.2.1 Geometric correction

All the IRS images are not geocoded and registered so in order to work with the satellite images, it is necessary to register the images with respect to Datum WGS 84. The image-image registration has been done in ERDAS IMAGINE 9.2.

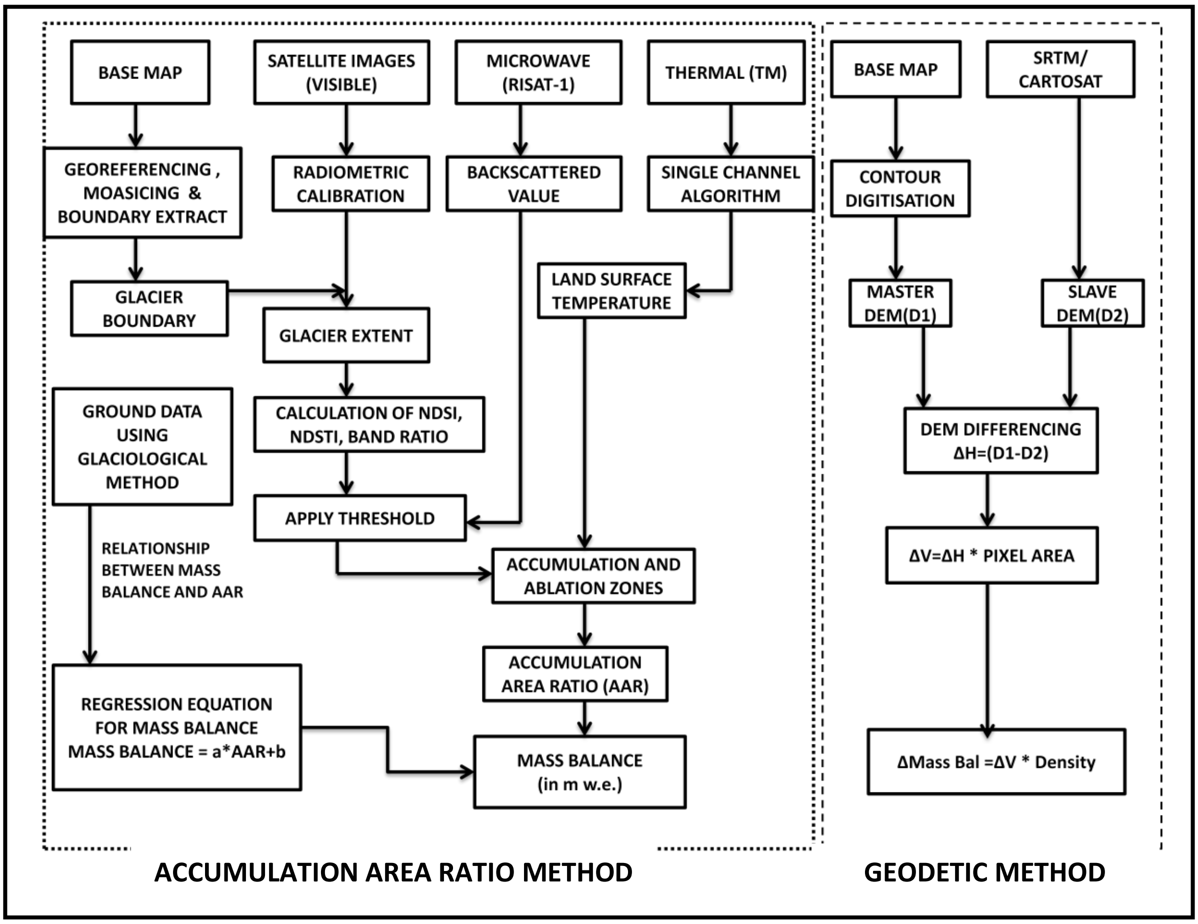


Figure 5.2: *Overall Methodology for Glacier mapping and Glacier Mass balance Estimation*

5.2.2 Radiometric Correction

Once the entire image dataset gets geometrically corrected, and then there is need to apply radiometric correction. Radiometric correction is a technique which involves the processing of digital remote sensed satellite images to improve the constancy of the brightness value magnitudes. Inconsistencies in the brightness values of image usually limits one's ability to interpret and analyses the remote sensed satellite image, so to reduce such errors and inconsistencies , there is need to apply radiometric correction on satellite images. Usually such errors and in consistencies are known to be as noise, which is considered as undesirable spatial and temporal variation in the brightness value of image which is not mainly associated with the image.

In multi-temporal imagery, radiometric consistency among ground targets is difficult to maintain due to changes in, atmospheric condition, solar angle, sensor characteristics and sensor view angle (Lillesand & Kiefer, 1994). Therefore, it is necessary to perform radiometric correction on multi-temporal imagery to reduce all of the above influences and increase the sensitivity to changing landscape (Chen *et al.,* 2005).

There are basically two type of radiometric correction:

1. Absolute correction
2. Relative correction

Absolute correction

Absolute radiometric correction is aimed towards extracting the absolute reflectance of scene targets at the surface of the earth. This method requires the input of simultaneous atmospheric properties and sensor calibration, which are difficult to acquire in many cases, especially in historic data.

Digital sensor record intensity of electromagnetic radiation of Earth Surface as Digital number (DN value) which in turn depends on the radiometric resolution of sensor (Green et al., 2000). In general LISS III, TM, ETM has radiometric resolution of 7 bit so it can store DN values in the range of 0-255. But the spectral signature of the Earth surface is not measured by the DN values. As spectral signature of the surface depends mainly on location of sun, viewing geometry of the satellite at moment the image has taken, and earth to sun distance. So it is necessary to convert all the DN values to radiance and reflectance.

Conversion of DN (digital number) value to Radiance

Digital numbers are converted into at sensor radiance with the help of respective sensor parameters present in the header file of the data. The general equation is as:

$$L_{sensor} = \frac{L_{max} - L_{min}}{Q_{calmax} - Q_{calmin}} * \left(Q_{cal} - Q_{calmin}\right) + L_{min} \dots\dots\dots\dots\dots (5.1)$$

Where,
L_{sensor} = Spectral radiance at sensor level [(W/m^2/sr/µm)]
L_{max} = maximum detected spectral radiance [(W/m^2/sr/ µm)]
L_{min} = minimum detected spectral radiance [(W/m^2/sr/ µm)]
Q_{ca}l = digital number for analysed scene
Q_{calmax} = maximum possible DN value (for dataset used, It is 255)
Q_{calmin} = minimum possible DN value (for dataset used, It is 0)
The value for L_{min} and L_{max} is different for different band for different satellite. These values are generally present in the header or leader file of the data.

Conversion of At-Sensor Radiance to Reflectance

The At-Sensor Radiance is further converted to Top of Atmospheric Reflectance which can be evaluated as per given formula

$$\mathrm{TOA} = \frac{\pi * \mathrm{Lsensor} * d^2}{E_{sun} * \cos\theta} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.2)$$

Where

TOA = Top of Atmospheric Reflectance [unitless] Lsensor = Spectral Radiance at Sensor Level [(W/m^2/sr/µm)] d = Earth sun distance[astronomical unit]; E_{sun} = Mean Exoatmospheric solar irradiance[(W/m^2/ µm)] θ = Solar zenith angle (degrees)

Table 5.1: *Ancillary information obtained through metadata of satellite images used to do Study*

Date of Pass	***Satellite and Sensor***	***Lmax and Lmin***			***Row/ Path***	***E_{sun} in $W/m^2/sr$***	***Sun Elevation Angle***	***Julian Day***	***Earth to Sun Distance***
		Band	Lmin	Lmax					
17 Aug 1997	IRS-1C (LISS-III)	B2	0.00	14.45	95/ 48	1851.1	65.23	229	1.0121
		B3	0.00	17.03		1583.8			
		B4	0.00	17.19		1102.5			
5Sept 1998		B5	0.00	2.42		240.40	60.23	248	1.00775
28Aug 2000	LANDSAT (ETM)	B1	-6.20	293.7	147/38	1969	58.33	241	1.00947
		B2	-6.40	300.9		1840			
		B3	-5.00	243.4		1551			
		B4	-5.10	241.1		1044			
		B5	-1.00	47.57		22.5			
		B6	0,	17.04		------			
			3.2	12.65					
		B7	-0.35	16.54		82.07			
		B8	-4.70	243.1		1368.0			
23Aug 2005	IRS-P6 LISS-III	B2	0.00	18.471	95/ 48	1849.5	63.48	235	1.01040
		B3	0.00	18.179		1553			
		B4	0.00	20.695		1092			
		B5	0.00	3.397		240.40			
26Aug 2006	IRS-1D LISS-III	B2	0.00	20.310	95/ 48	1852.2	55.01757	238	1.010174
		B3	0.00	15.664		1577.3			
		B4	0.00	16.452		1096.7			
		B5	0.00	2.4381		240.60			

20 Aug 2008							42.441	233	1.01128
13 Aug 2009 16 Aug 2010	LANDSAT TM	B1 B2 B3 B4 B5 B6 B7	-1.52 -2.84 -1.17 -1.51 -0.37 1.28 -0.15	193.0 365.0 264.0 221.0 30.20 15.303 16.5	147/ 38	1957 1826 1554 1036 215 ----- 80.6	60.94 60.648	225 228	1.01286 1.01229

5.3 Mapping Techniques

Now days, there is issue to worry about the disappearance of glaciers due to global warming and hence causing global change. As it has been said that glaciers are highly sensitive and affected by climate very easily. So, monitoring of snow cover and assessment of the changes that affect glacier health are in high demand as it is required for the water security of nation (Negi *et al*, 2012).

Mapping of accumulation and ablation zones of glacier can be done using remote sensing.

As accumulation area consists of snow and ice and snow has different spectral signature in optical data which is easily mappable and identifiable on the satellite images. As satellite data can view large area and multi temporal satellite images help in the monitoring of the seasonal change in snow cover, therefore technique of remote sensing proved to be helpful in providing information on accumulation and ablation of snow cover rather than any conventional technique (SAC, 2010).

But the major difficulties in monitoring and mapping the glaciers zones in the Himalayas region is mountain shadow and intense cloud cover in the visible and infrared region. Because of these reasons combination of digital and visual interpretation is needed (Kulkarni, 2002). But there are some automated techniques which overcome the effect of shadowing and cloud covering. Based on remote sensing this study include the mapping of zone of glacier with optical, thermal and microwave remote sensing data.

5.3.1 Optical remote sensing

Glacier surface is composed of snow, firn, ice, and debris, these significantly affect the optical properties of glacier. The spectral properties of snow show high reflectance in visible part with high dependency on impurities and small dependency on grain size and decreases in the NIR region and very low reflectance in middle infrared (Pellika and Rees, 2010). The zone of glacier has been differentiated using basically two techniques:

1. Normalised Snow Difference Index (NDSI).
2. Band Ratio.

5.3.1.1 Normalized Difference Snow Index (NDSI)

Normalized Difference Snow Index is found to be very effective in mapping of snow and non snow cover area. This algorithm uses the reflectance values of snow. Generally the snow show very reflectance in visible region and appear white in colour while in SWIR region it has very low reflectance and generally appear black. Due to this notion, NDSI is proved to a useful index for discriminating snow and clouds as cloud show even high reflectance in SWIR region (Kulkarni et.al, 2002). It also have been proved that NDSI values can be used to identify snow or non-snow pixels under mountain shadow region to some extend and under any orientation i.e. it is independent of illumination condition. (Kulkarni et. al., 2006). NDSI is generally estimated using the Equation (Hall.et al. 2002b).

$$\text{NDSI} = \frac{\text{Green Band Reflectance} - \text{SWIR Band Reflectance}}{\text{Green Band Reflectance} + \text{SWIR Band Reflectance}} \ldots\ldots\ldots\ldots (5.3)$$

Generally value of NDSI range from -1 to 1.Using corresponding bands in different sensors, NDSI value is determined. Based on the visual interpretation and their respective NDSI values appropriate threshold is applied which automatically delineate the accumulation and ablation zones. Since due to the topographic effect sometimes manual delineation need to be done on this automated techniques. In the studied dataset for LISS, band 1 and band 4 is used to calculate NDSI, while in case of ETM and TM, band 2 and band 5 is used.
For LISS-III:

$$\text{NDSI} = \frac{\text{Band1} - \text{Band4}}{\text{Band1} + \text{Band4}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.4)$$

For Landsat ETM &TM

$$\text{NDSI} = \frac{\text{Band2} - \text{Band5}}{\text{Band2} + \text{Band5}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . \ldots (5.5)$$

5.3.1.2 Band Ratio

Band ratio is also one of the semi automated techniques used for glacier mapping. The NIR/SWIR has been shown to be effective in discriminating ice and snow faces particularly in shadow area (Hall, 1987). Paul (2001) concluded that NIR/SWIR (TM4/TM5) ratio techniques are appropriate for clean ice glacier mapping. The main advantage of using visible and near infrared data is the easy interpretation of the image (Haq, 2012). In case of LISS the band 3 (NIR) and band 4 (SWIR) is used while in case of Landsat TM and ETM band 4 (NIR) and band 5 (SWIR) is used.

$$\text{Band Ratio} = \frac{\text{NIR Band Reflectance}}{\text{SWIR Band Reflectance}} \ldots\ldots\ldots\ldots . \ldots (5.6)$$

On applying appropriate range of threshold on band ratio, accumulation and ablation areas get separated. This ratio was evaluated mostly on DN values and generally threshold of 1-2 is applied. But this study has evaluated the ratio based on reflectance of their respective accumulation and ablation zones of glaciers. Selection of threshold value is one of crucial job because a small variation leads to under or over estimation of snow cover. Threshold may also varies from one satellite sensor to another.(hall.et.al,1995, Dozier,1989).

In the studied dataset for LISS, band 3 and band 4 is used to calculate Band Ratio, while in case of ETM and TM, band 4 and band 5 is used.

For LISS-III

$$\text{Band Ratio} = \frac{\text{Band3}}{\text{Band4}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5.7)$$

For Landsat ETM &TM

$$\text{Band Ratio} = \frac{\text{Band4}}{\text{Band5}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5.8)$$

These mapping techniques give us time series of accumulation and ablation areas when applied on the available dataset.

5.3.2 Thermal remote sensing

Thermal infra red is proved to be very powerful technique for distinguishing surface object using land surface temperature and emissivity (Rees, 2010). The TIR possesses the capacity to map glacier since the surface temperature so emitted is usually consider to be function of the heat conducted from below to the glacier surface. Land Surface Temperature is evaluated using 6 band of Landsat TM. This study has done to do zonation of glaciers by applying Single Channel Algorithm using water vapour content and emissivity. The most recent technique where the thermal band play an important role is the development of new index i.e. NDSTI. In this study, two different techniques is used to map glacier zones by thermal remote sensing and these are:

1. NDSTI
2. Land Surface Temperature

5.3.2.1 Normalised Difference Snow Thermal Index (NDSTI)

It stands for Normalised Difference Snow Thermal Index (NDSTI). This newly developed index uses visible, thermal-infrared radiance. NDSTI is evaluated by the ratio of discriminating bands and normalizing the pixel values to within standard range which will give sensitive and comparable test of thermal character. Since dividing the values of two spectral band by each other is one of the common image processing techniques. If the ratio is small, change will be small on the other hand if ratio is large, causing large spectral difference. This kind of ratioing techniques used in many applications for example for the identification of minerals and the earth ores.

The newly proposed NDSTI is proved to be useful for the identification of ice and snow and for differentiating ice/snow from surrounding features. The NDSTI is defined as the ratio of difference of radiance observed in a visible band (blue) and the Thermal infrared (TIR) band to the sum of their radiance value. NDSTI normally uses the spectral behaviour of ice/snow which shows high reflectance in the visible region and strong absorption in the TIR region and it does not rely on radiance of a single band. Before estimating ratio, resampling of TIR band was performed with respect to visible band. The TIR wavelength range of 10.40–12.50

µm (Landsat Band 6) has usually been used for the evaluation of the NDSTI under as (Development of New Thermal Ratio Index for Snow/Ice Identification).

$$\text{NDSTI} = \frac{\text{Blue Band Reflectance} - \text{TIR Band Reflectance}}{\text{Blue Band Reflectance} + \text{TIR Band Reflectance}} \ldots\ldots\ldots\ldots (5.9)$$

5.3.2.2 Land Surface Temperature

Thermal remote sensing is recognized to be source of quantative and qualitative Information on land surface processes. (Jiménez-Muñoz et al., 2009). Land surface temperature is one of the key variables associated with the many land surface processes, is usually derived from the thermal remote sensing. (Chen *et al*., 2011) This study evaluates LST from Single Channel Algorithm which help in the mapping of further different zones of glacier on the basis of temperature difference. The key atmospheric parameters needed to estimate LST is Emissivity, Water vapour Content. Since this algorithm is mainly applied to work for Landsat TM, so in data set have satellite image i.e. 16 Aug 2010, used to apply algorithm. LST is one of the satellite products whose resolution is very low and it is suitable over large area also but to estimate LST over small area, there is a need to use some specialised algorithm.

The main Equation for the Estimation of Single Channel Algorithm are:-

$$\mathbf{T_s = \gamma\left[\frac{1}{\varepsilon}(\psi_1 L_{sen} + \psi_2) + \psi_3\right] + \delta} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.10)$$

Where ε is the surface emissivity.γ & δ are two parameters mainly dependent dependent on the Planck's function. ψ1, ψ2, and ψ3 are referred to as AFs. $L_{sen =}$ at sensor radiance. L_{sen} has been calculated using gain and bias value of the sensor

In case of landsat TM

lmin= 1.2378 and lmax=15.303 (in W / (m^2sr.µm))

So, we calculate gain and bias as

Gain = (15.303 – 1.2378)/255 = 0.055158

Bias = 1.2378.

Using gain and bias, at sensor has been calculated as(A C++ program for retrieving land surface temperature from the data of Landsat TM/ETM+ band6):

$$L_{sen} = \text{gain} \times \text{DN} + \text{Bias} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.11)$$

Radiance value got from Landsat TM is transformed into at sensor Top of atmospheric Brightness temperature. It has been evaluated using equation derived from inversion of Planck's law which is as:

$$T_{sen} = \frac{c_2}{\lambda \ln\left(\frac{c_1}{\lambda^5 L_{sen}} + 1\right)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.12)$$

Value of λ for landsat 5 TM is 11.457µm.

The value of intermediate parameters δ (delta) and γ (gamma) are mainly depend on wavelength, $T_{sen,}$, $L_{sen,}$ which is summarized below:

$$\gamma = \left\{\frac{c_2 L_{sen}}{T_{sen}^2}\left[\frac{\lambda^4 L_{sen}}{c_1} + \frac{1}{\lambda}\right]\right\}^{-1} \ldots\ldots\ldots\ldots\ldots\ldots. (5.13)$$

This equation can be rewritten into:

$$\gamma = \frac{T_{sen}^2}{\alpha_\gamma L_{sen}^2 + b_\gamma L_{sen}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.14)$$

Where $$\alpha_\gamma \equiv \frac{c_2 \lambda^4}{c_1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (5.15)$$

$$b_\gamma \equiv \frac{c_2}{\lambda} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.16)$$

Where the value of $c_1 = 1.19104 * 10^8$ Wμm^4 m^{-2} sr^{-1} and $c_2 = 14387.7$µmK.

Once gamma is evaluated then next step is the evaluation of delta which depends on delta and other parameter can be evaluated as:

$$\delta = -\gamma L_{sen} + T_{sen} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (5.17)$$

The main equation needs the atmospheric function which depends on water vapour content. The water vapour content can be derived from AIRES which has 1^0 resolutions.

For Landsat 16 Aug, 2010, the water vapour content comes out to be 1.2133g/cm^2

As it is necessary to know that

$\psi_1 = 1/\tau$, $\psi_2 = - L^{\downarrow} - L^{\uparrow}/\tau$, $\psi_3 = L^{\downarrow}$

Where $L^{\downarrow}$ means downwellling radiance and $L^{\uparrow}$ means upwelling radiance and τ means transmitivity (Jiménez-Muñoz et al., 2009). These atmospheric parameters are not easy to calculate or estimate. So, the practical technique used in single channel algorithm is that approximation of atmospheric function of ψ_1, ψ_2 and ψ_3 versus atmospheric water vapour content from second order polynomial degree (Jiménez-Muñoz et al., 2009).

$$\begin{bmatrix}\Psi_1\\ \Psi_2\\ \Psi_3\end{bmatrix} = \begin{bmatrix}c_{11} & c_{12} & c_{13}\\ c_{21} & c_{22} & c_{32}\\ c_{31} & c_{32} & c_{33}\end{bmatrix}\begin{bmatrix}w^2\\ w\\ 1\end{bmatrix}$$

There are many sounding atmospheres which has atmospheric profile. Since TIGR 61 have distributed database of water vapour while other TIGR 2311 and TIGR 1761 are suitable and centred for low water vapour content around 1g/cm^2. So, for study we selected TIGR 61. And for Landsat5TM 6 band the AF can be taking as:

$$\Psi_1 = 0.14714\,w^2 - 0.15583\,w + 1.1234$$

$$\Psi_2 = -1.1836w^2 - 0.37607\,w - 0.52894$$

$$\Psi_3 = -0.04554W^2 + 1.8719\,w - 0.39071$$

Which comes out to be as:-

$$\Psi_1 = 1.152291$$

$$\Psi_2 = -2.74942$$

$$\Psi_3 = 2.215936$$

The last parameter that needs to be known for solving Land surface Temperature Equation is Emissivity. Since Emissivity is varied according to time and surface in contact. As our glacier is consists of snow, ice, ice with debris, debris cover so, emissivity values taken as using source is as under:

Once every parameter is evaluated, the LST can be estimated for both the time periods.

Thresholding

After calculation of NDSI and Band Ratio, there is need to calculate proper thresholding value to separate the glacier zones, which can be estimated using pixel value of snow line. The application of threshold wholly a visually interpretation technique. Based on the visual interpretation and their respective NDSI or Band ratio values appropriate threshold is applied which automatically delineate the accumulation and ablation zones of glaciers. Since due to the topographic effect sometimes manual delineation need to be done on this automated techniques. The range of threshold applied on the dataset to discriminate zones in NDSI is from 0.4 to 0.8. Selection of threshold value is one of crucial job because small variations lead to under or over estimation of snow cover. Threshold may also vary from one satellite sensor to another. (Hall et.al, 1995 Dozier, 1989). On thresholding accumulation and ablation zone get separated. Sometimes due to cloud and topographic effect, manual delineating need to be done based on visual interpretation. As a result of thresholding, the accumulation and ablation zones get the value of 1 and 0. The count value in the raster attribute table give the number of pixels of the respective zones. On multiplying the number of pixel of accumulation zones with the pixel size (resolution) give the accumulation area. Similar practice has been done for ablation area calculation:-

Accumulation area = pixel count for value 1 * pixel size * pixel size

5.3.3 Microwave Remote Sensing

RISAT-1 Data normally has been used for this study. The RISAT data was not geocoded so, for mapping glacier it was necessary to georegistered. Once it is georegistered, the next step is to create intensity image. The intensity map give backscattered value based on which we differentiate dry and wet zone in SAR image. Since the Snowline is evaluated is around 4810, but since mass balance is estimated at the end of ablation season, so the snowline is assumed to get approximate mass balance by manual digitisation of accumulation area.

5.4 Estimation of Mass Balance Using AAR Method

5.4.1 Relationship between AAR and Mass Balance

As per Previous Scientific studies it has been concluded that the accumulation–area ratio i.e. (AAR = Sc/S, where Sc is accumulation area and S the total glacier area) changes with change in annual (or net) glacier mass balance B (Dyurgerov and Meier, 2005). This interrelationship deduces that the change in glacier accumulation areas can be estimate in context to mass-balance changes and to a certain extent, due to change in climate. (a new index). This study establishes a mathematical model among the actual mass balance, total glacier extent and accumulation area collected in between 2002-2010 on Chhota Shigri Glacier, Based on the field investigation, specific mass balance between year 2002-2010 is estimated by Wagnon et, al.2007; JNU-SAC, 2008; JNU- IFCPAR, 2009, 2010 which is reported in Himalayan Glaciology Technical Report as “STATUS REPORT ON CHHOTA SHIGRI GLACIER” (HIMACHAL PRADESH) is shown in table 5.1 (Ramanathan, 2011). The study uses this data and establish a mathematical model between Specific mass balance and AAR as a regression equation of **0.0386*AAR – 2.5000** with $\mathbf{R^2 = 0.95}$ as in figure5.3. This mathematical model then use the AAR derived from the dataset used for the study. This model help in the validation of the remote sensing based derived AAR and mass balance with the ground data. Using Remote sensing approach, Accumulation zone of glaciers for satellite images 1997, 1998, 2000, 2005, 2006, 2008, 2009, 2010 are calculated using NDSI and Band ratio techniques which further used to calculate AAR and further mass balance of glacier.

Once accumulation area and total area of the glacier for all the dataset has been estimated the next step is the estimation of AAR. For each satellite image, depending on the accumulation area the value of AAR changes. AAR is evaluated by applying threshold to NDSI and Band Ratio. The value of threshold is approximated easily if snowline or ELA is already known. SLA is easily identifiable in the optical satellite image,

Table 5.2: *Specific mass balance for 2002 – 2010 (Source: Wagnon et al,. 2007; JNU-SAC, 2008 ; JNU- IFCPAR, 2009,2010; JNU- DST, 2011)*

S.NO	YEARS	AAR VALUE (%)	MASS BALANCE (m w.e.)
1	2003	31	-1.4
2	2004	31	-1.2
3	2005	74	0.1
4	2006	29	-1.4
5	2007	36	-1.3
6	2008	37	-0.93
7	2009	63	0.13
8	2010	70	0.33

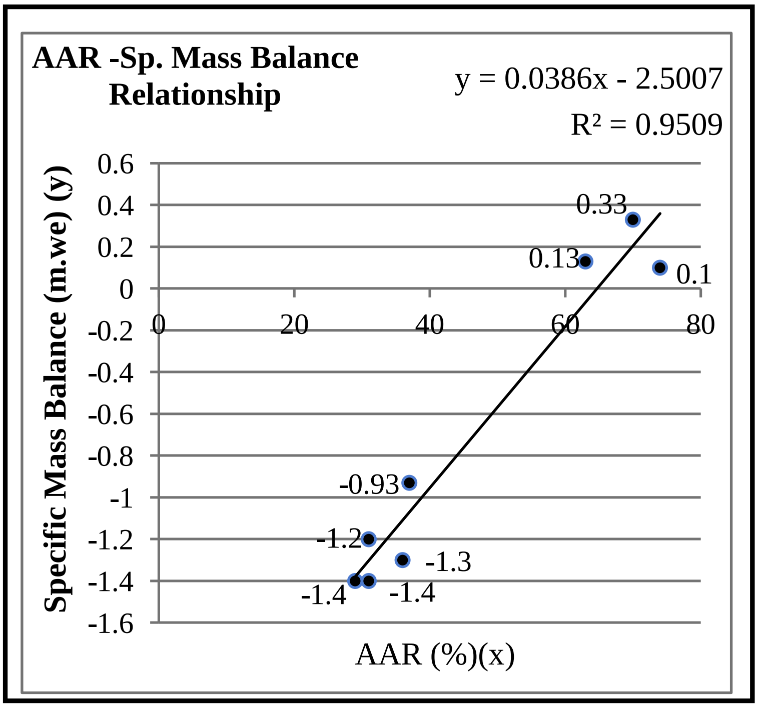


Figure 5.3: *Mathematical model derived from the relationship between mass balance and AAR with y = 0.0386*x – 2.5007 with coefficient of correlation is 0.95*

Difficulty arises in the microwave region when accumulation area overlay with the ablation zone or accumulated zone is wet. Even AAR also shows direct relationship with SLA, if the

SLA line is high i.e. high elevation during melting season, then area accumulation ratio is less, the mass balance can be negative. On the other hand if snowline found to be at low elevation, the area under accumulation zone is large resulting in positive mass balance. The value of SLA also contributes a lot in the mass balance estimation. But exact value of SLA is not estimated, its value can only be approximated, elevation changes along the snowline.

5.4.2 Snowline Estimation from DEM

The study also has estimate approximate SLA using SRTM DEM, assuming that elevation change for datasets is negligible. Digitisation of snow line for all the dataset under study has been done. Several points on the digitised snowline for different years has been taken, averaging of elevation of all point on a single snowline give the approximate snowline altitude for that time period with some deviations. The fig. shows the digitised snowline for different years. Here in the fig, some ground control points collected during field (26 September, 2012) are shown below.

After the ELA and AAR calculation, the last step is mass balance estimation, Using different values of AAR for different satellite images, Annual Mass balance of the glacier can be estimated for particular time period using the regression model so evaluated as:-

Annual Mass balance = 0.0386 * AAR – 2.5000……………… (5.18)

The AAR used should in percentage (%). The Mass balance of Glacier Mass Balance so evaluated is matched with the ground data and error estimation has been done.

5.5 Estimation of Mass Balance Using Geodetic Method

Mass balance can be estimated through Geodetic Method. In geodetic method, study need Digital elevation for two time period which have time difference of more than a decade. Since Master DEM have been created using digitisation of contours at 40 metre interval from reprojected mosaic Base map of 1966. Since SRTM DEM also used as Slave DEM acquired 2002 with cell size resampled from 90 meters to 30 meters. Interpolation has been done with nearest neighbour and resample at 30 metre cell size. The two DEM are in Raster format. These DEMs need to be subtracted to get the Elevation Difference. This Elevation difference on multiplying with Pixel size gives volume at pixel level. On getting volume at pixel level, it is multiplied with density of glacier to get mass balance.

5.6 Customization of GUI

An effort has been made to use Semiautomatic techniques of NDSI and Band Ratio for separating Glacier zones. Also in order to calculate glacier mass balance by AAR method and Geodetic method using Remote sensing approach customization of a tool in open source programming language has been done to provide an aid to people who usually are not aware to work with GIS environment and programming language. The description of Graphical User Interface has been summarized in detail in chapter 6.

6. Graphical User Interface Tool for Glacier Mass Balance Estimation: “GEOSPATIAL TOOL FOR GLACIER MASS BALANCE ESTIMATION”

6.1 Need for GUI Development

Estimation of glacier mass balance is a challenging task as it requires a lot of field work. But with the advancement in the field of remote sensing and Image processing it becomes feasible to apply semiautomatic techniques and algorithms on satellites and derive some parameters through which mass balance can be estimated.

A simple tool has been developed to perform some basic image processing functions required to deal with the satellite images and try to developed a linear relationship between the AAR and mass balance if derived from Ground data, based on which mass balance can be calculated.

The gui/tool is developed in Python progranmming language using open souce libraries of GDAL, Numpy, Matplotlib etc. This tool is developed to provide an ease to non programmer to work well on satellite images who are not comfortable with GIS softwares

The tool try to estimate mass balance by

- AAR Method
- Geodetic Method

The tool is purely open source software.

6.2 Overview of the Software

The software basically subdivided into 3 basic modules which conatins Image processing module, Regression Module, Mass balance estimation. All the module are dependent on each other. Image works on optical data only. The image processing includes function like stacking, clipping, calculation of radiance and reflectance, band ratioing and masking. Regression module has main function of establishing relationship between parameters needed to calculate mass balance. Mass balance estimation can be obtained by thresholding approach and DEM differencing Approach. This software give the appoximation as well as range of mass balance when different threshold applied on the images. The image view feature is not yet develop. So, user in order to see these image can use QGIS. The tool also provide Step wise Step processing needed to be done in “help” button at the bottom left of each page.

Figure 6.1 shows the home page of tool developed with name “ Glacier Mass Balance Estimation In Geospatial Environment”. Home page has basically three button

1. On pressing “AAR METHOD”, the user will switch on the “Image Stacking” page as this it is the first step for the estimation mass balance when we get raw data.

2.On pressing ”Geodetic Method” button, the user will switch onto the Geodetic mass balance page.

3. On pressing “ABOUT “ button, it will give the information about the current page opened. Figure 6.2 shows us information when ABOUT button is clicked.

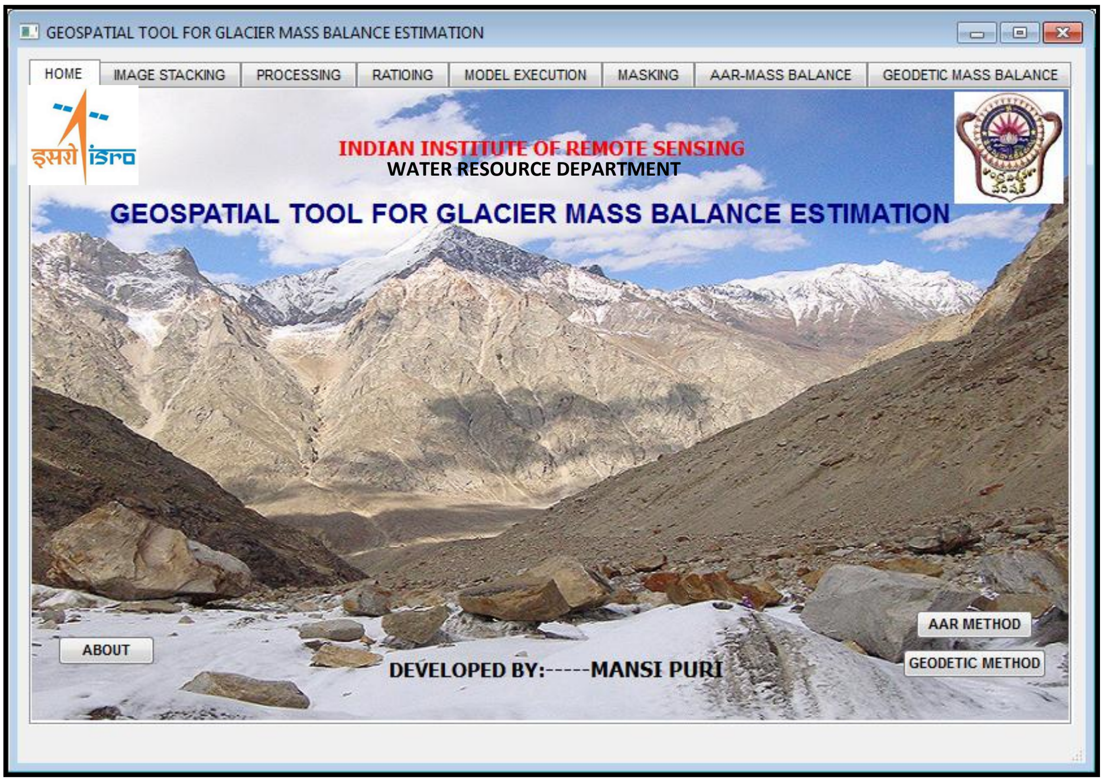


Figure 6.1: *Home page of software ”GEOSPATIAL TOOL FOR GLACIER MASS BALANCE ESTIMATION”*

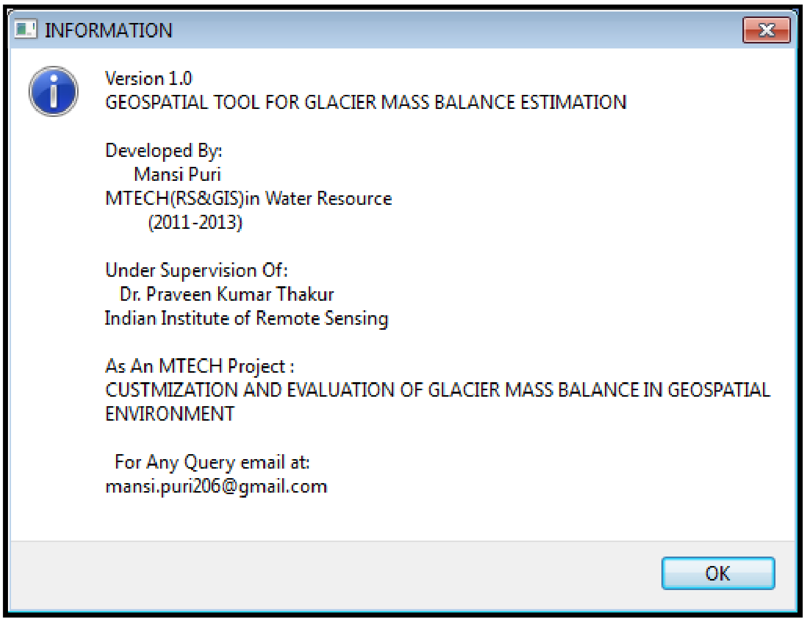


Figure 6.2: *Pressing “About” gives information about tool*

6.2.1 Stacking and Area of interest

On pressing tab “Image Stacking”, window opens same as in Fig 6.3. it has two sub parts as shown

1. Stacking

2. Area of Interest

Stacking

It allows user to input the select the folder where the raw images are stored. After selecting the location, the user need to show whether he want to do stacking on Landsat or LISS-III. The reason for radio button “Landsat” and “LISS-III”as for Landsat only stacking of six bands is possible while for LISS, only four bands will be stacked. After pressing radio button, list of names of images are shown. User makes selection of bands and produce output. The Output will be saved in the same location (input Folder Location) with name “OUT.TIF” when we press “STACK”.

On pressing STACK command prompt will open and perform

0...10…20…30…….40….50…60….70….80….90….100…done followed by message Box “Stacking Over”. The figure 6.3 and 6.4 shows the screenshots of layout of image stacking and stacking process going on command prompt respectively.

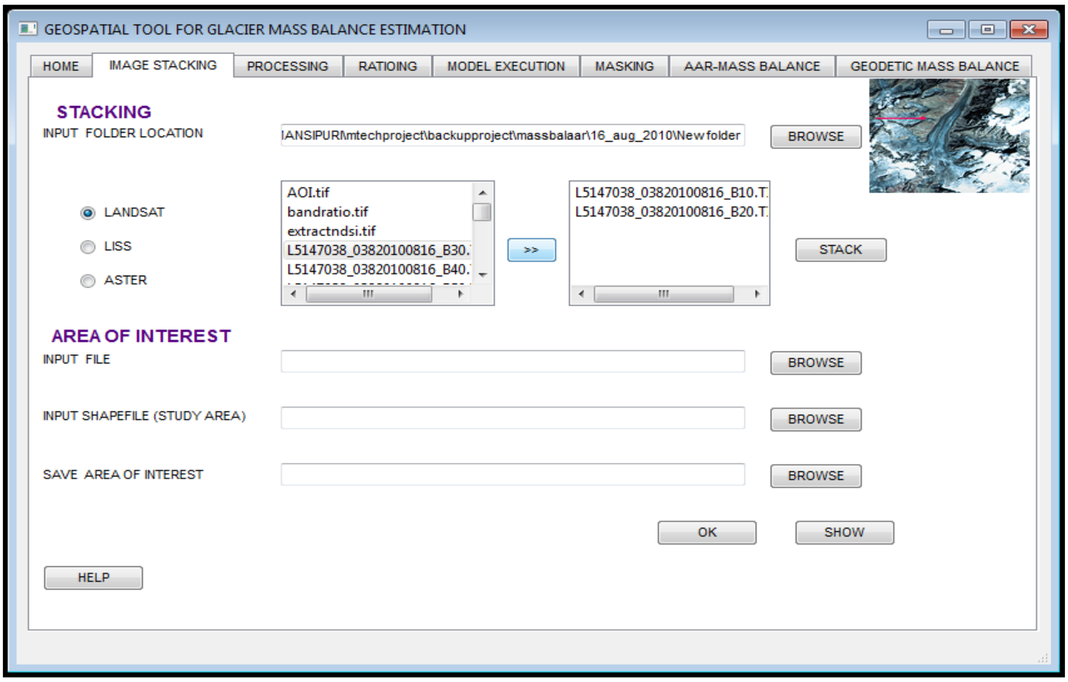


Figure 6.3: *Layout of Image Stacking and Area of Interest page*

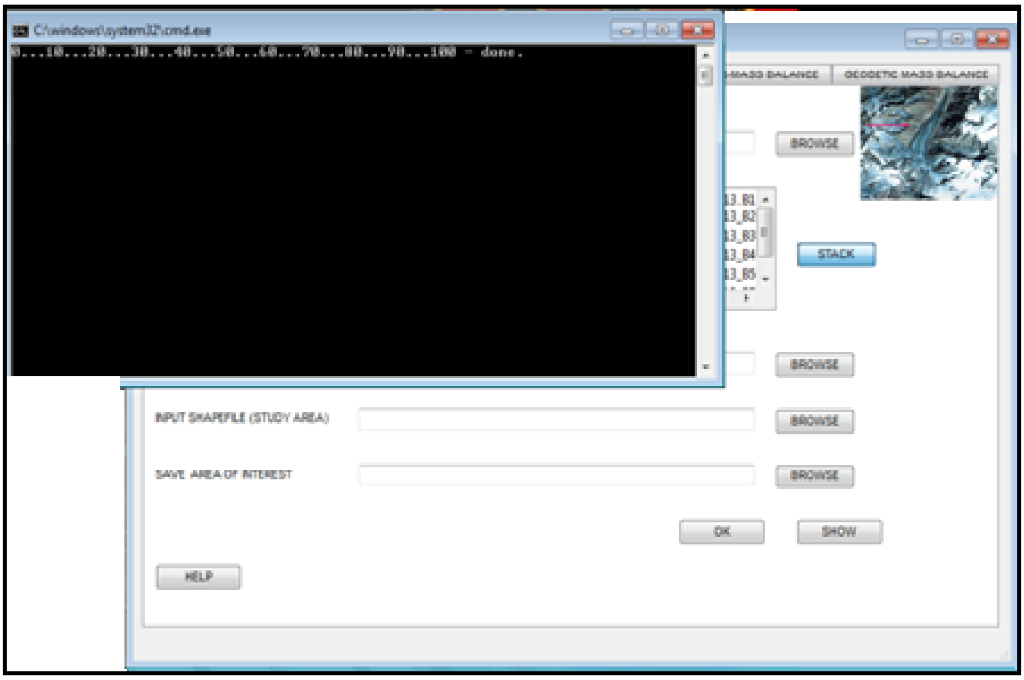


Figure 6.4*: Stacking process is going on command prompt*

Area of Interest

This operation is similar to “CLIP” operation. As in order to maintain the speed of the software there is need to do processing on certain part of image instead on whole image so area of interest same as the extent of shape file is obtained.

Input file: Input Out.tif file or any single .tif file

Input shapefile : Input the shapefile whose extent user want.

Output file: Give the location of output file.

Note: All the image and shape file should be properly georeferenced and with same projection system. The entire path name should not have space in their file or folder name.

Here we are using UTM WGS84 Zone 43.

6.2.2 Processing

In this tab user has choice to select the sensor, there are options for LANDSAT TM, LANDSAT ETM, IRS-1C, IRS -1D, and IRS- P6. User need to give Zenith angle and Enter the Julian day which is already present in its metadata file. User also has to input stacked and clipped output file obtained at the previous page. In order to calculate the radiance and reflectance as output user has to give folder location and name. This specific name will append in all the file generated based on the number of bands of sensors with extension of “band number.tif”. On pressing calculate button, it will give message “Please wait Process for “Sensor name” is going on” and followed by message “Process Complete”. Figure 6.5 give us layout of Processing tab used to calculate radiance and reflectance .

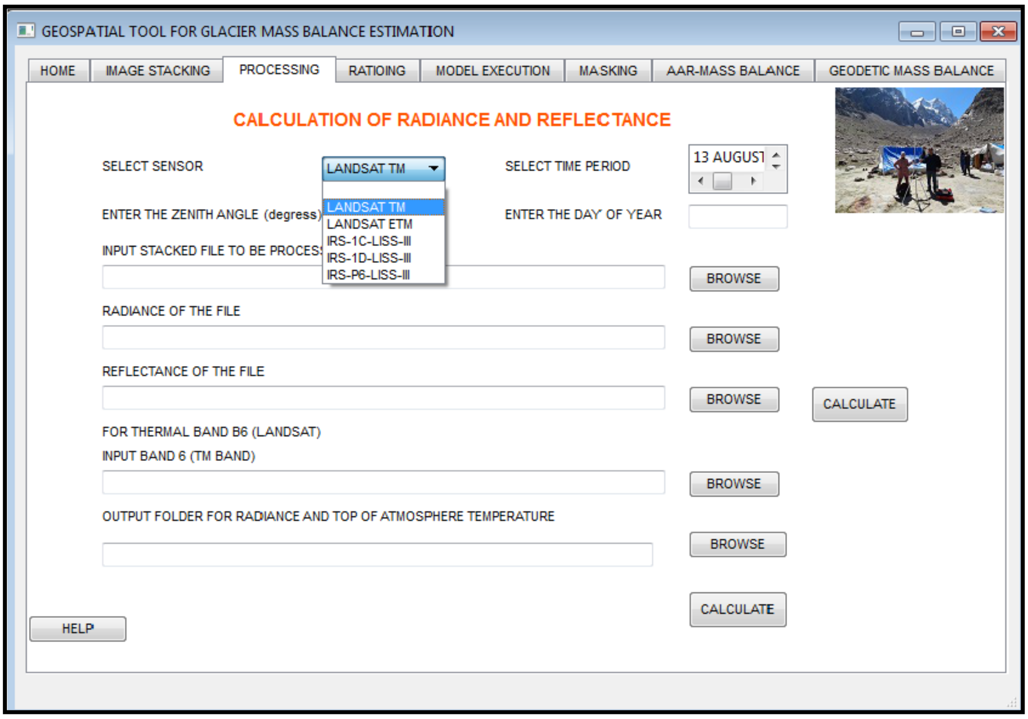


Figure 6.5: *Layout of the Processing tab performing calculation of radiance and reflectance*

Since this tool has option for calculating radiance and top of atmosphere temperature for band 6 as it contain different spatial resolution. But as per new policy launched by USGS, the raw data contain band 6 resample at 30 meters. So, user can have liberty to calculate the radiance separately or with the other bands too.

6.2.3 Ratioing

The user can perform ratioing of different bands i.e. can perform mathematics on images, when Ratioing tab is clicked.

User has to provide input as reflectance or radiance bands as need arises. Since the drop down menu gives user the choice to select mainly three ratios

1. NDSI (reflectance)

2. BANDRATIO (reflectance)

3. NDSTI (radiance)

On clicking any one of the options message will cm giving information about the sensor and bands user need to select for estimating particular index. After selecting required bands and particular operation, the user will need to provide output location and press calculate to run the code. Once the operation has done, message box pops out Message " Process Completed. The layout for the calculation of different ratios and indexes is given in figure 6.6. The information obtained after selecting different indexes in Dropdown box give user information about the sensor and bands used to calculate particular ratio or index which is depicted in figure 6.7.

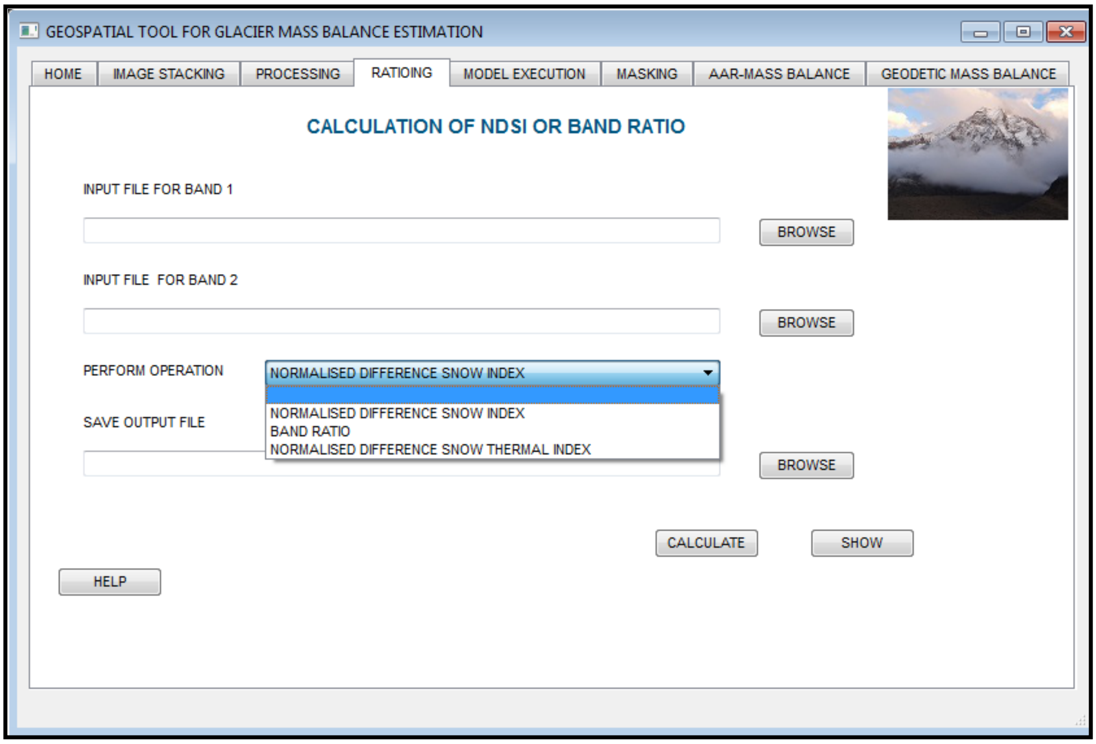


Figure 6.6: *Layout of Band Ratio*

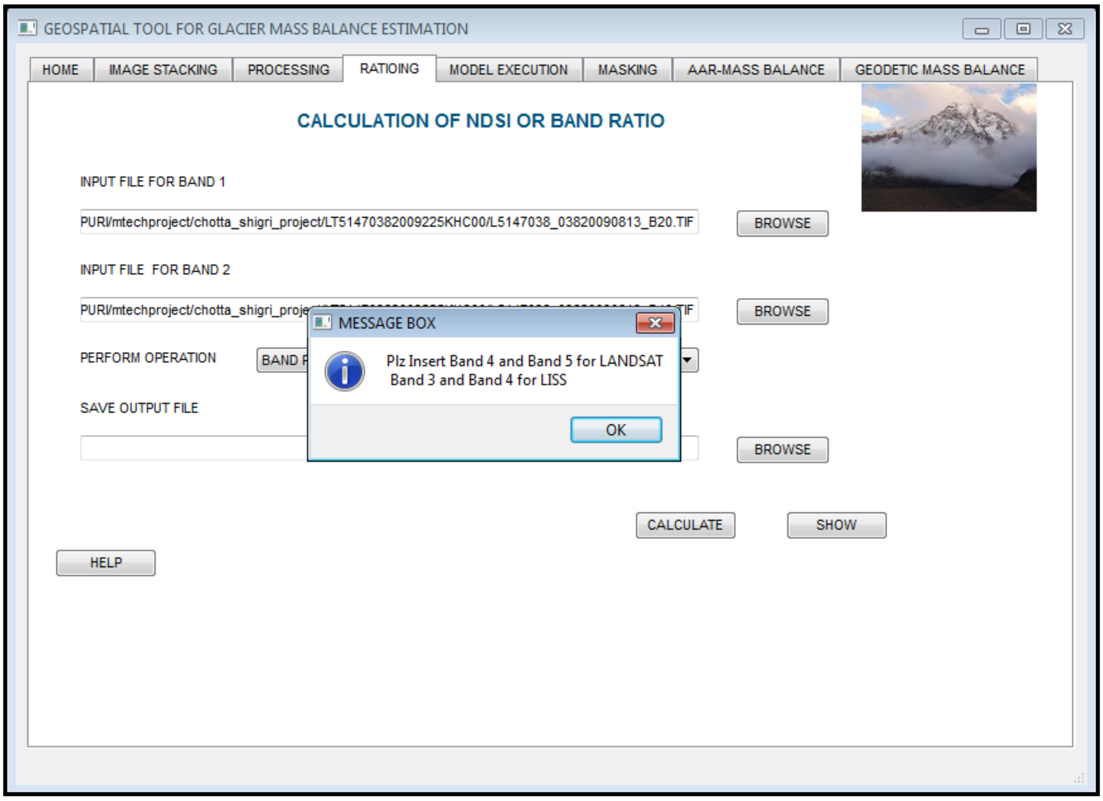


Figure 6.7: Information about bands of sensor for evaluating particular ratio

6.2.4 Regression Module

The Next Module is "REGRESSION MODULE" in which a regression model or relationship has been developed between the mass balance and AAR method.

Input file is the file containing data for AAR and mass balance which should be saved in ".csv" format. So, on clicking Regression model a relationship is established between AAR and mass balance which can be shown.

For Chhota Shigri glacier it comes out to be

Mass balance= 0.0386413* AAR-2.5007.

The figure 6.8 demonstrates the relationship generated through AAR and Mass balance for Chhota Shigri Glacier when parameter containing ".csv" file is given as input.

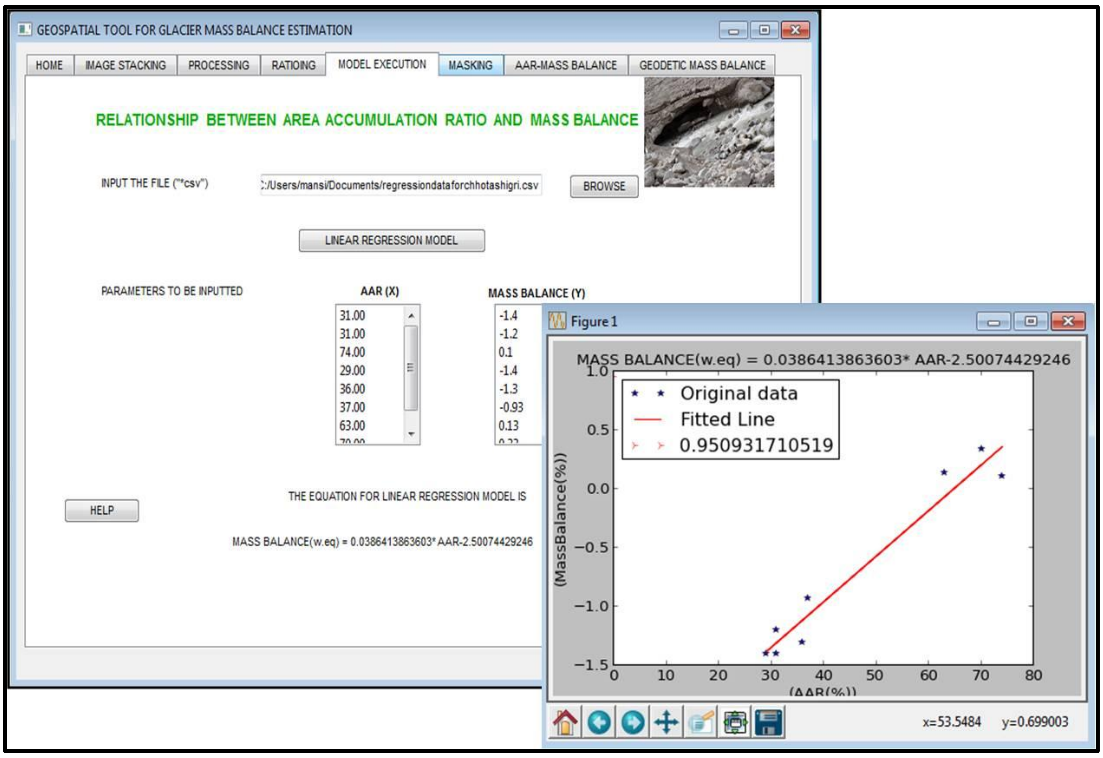


Figure 6.8: *Regression analysis in model execution tab resulting linear relationship between AAR and Mass Balance*

6.2.5 Masking

The next image processing needs to be done is masking. The input file is given to be the NDSI, Band Ratio or NDSTI image. User should also input the shapefile. This window works on function as "Extraction by shapefile." It will extract the area according to the shapefile. And output will be stored in the folder desired by the user. The process runs in a command prompt followed by a pop-up message "process complete". Figure 6.9 shows layout of the masking.

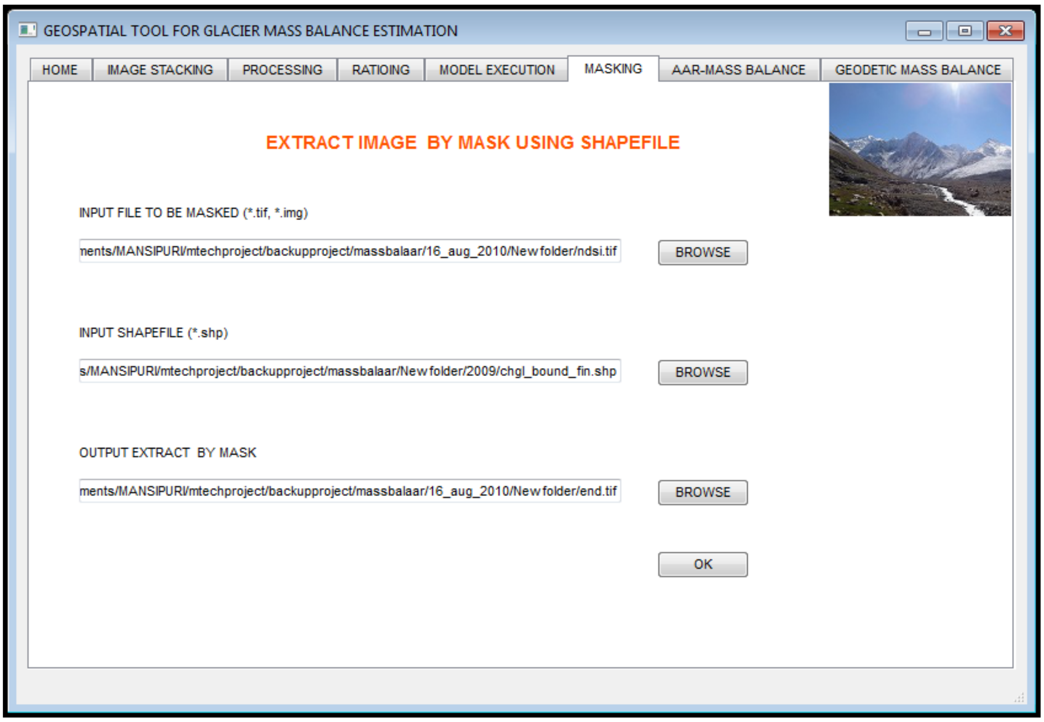


Figure 6.9*: Page Layout for Masking of Shapefile*

6.2.6 Thresholding

The next step is the estimation of Mass balance by applying thresholding to the NDSI, NDSTI, and BANDRATIO. Input the extracted file (NDSI, TM, and NDSTI). Apply the appropriate threshold and give output file name location.

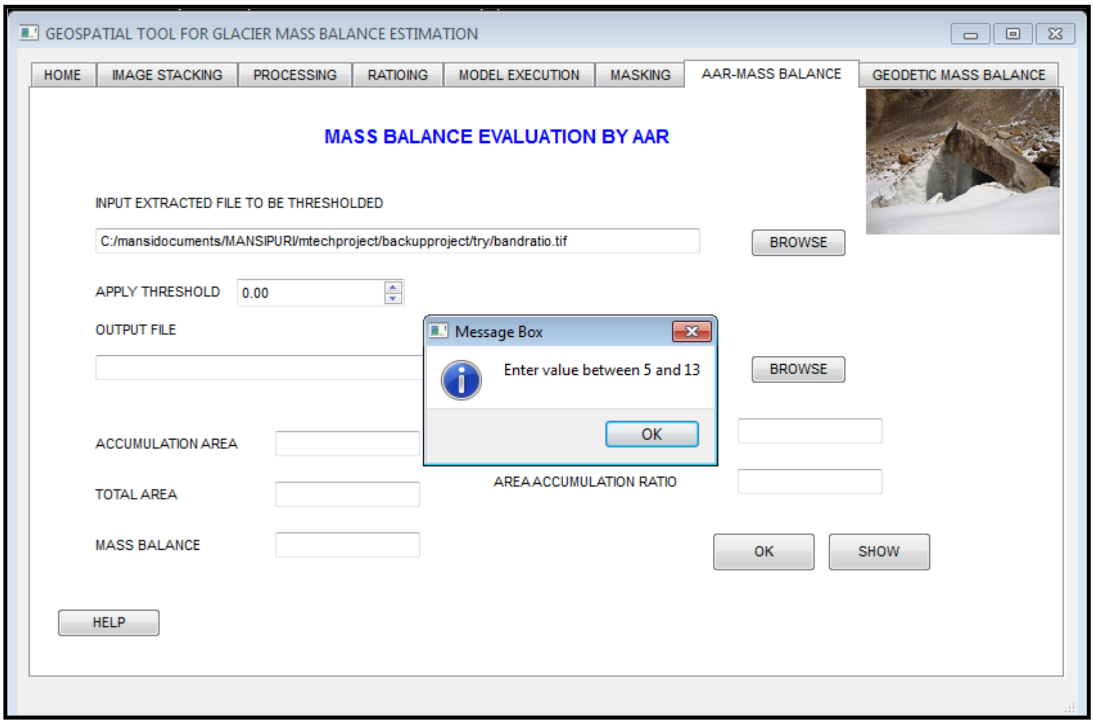


Figure 6.10: *Layout of thresholding and mass balance by AAR*

On clicking the “Ok” tab, accumulation area, ablation area, AAR and mass balance is calculated and displayed.

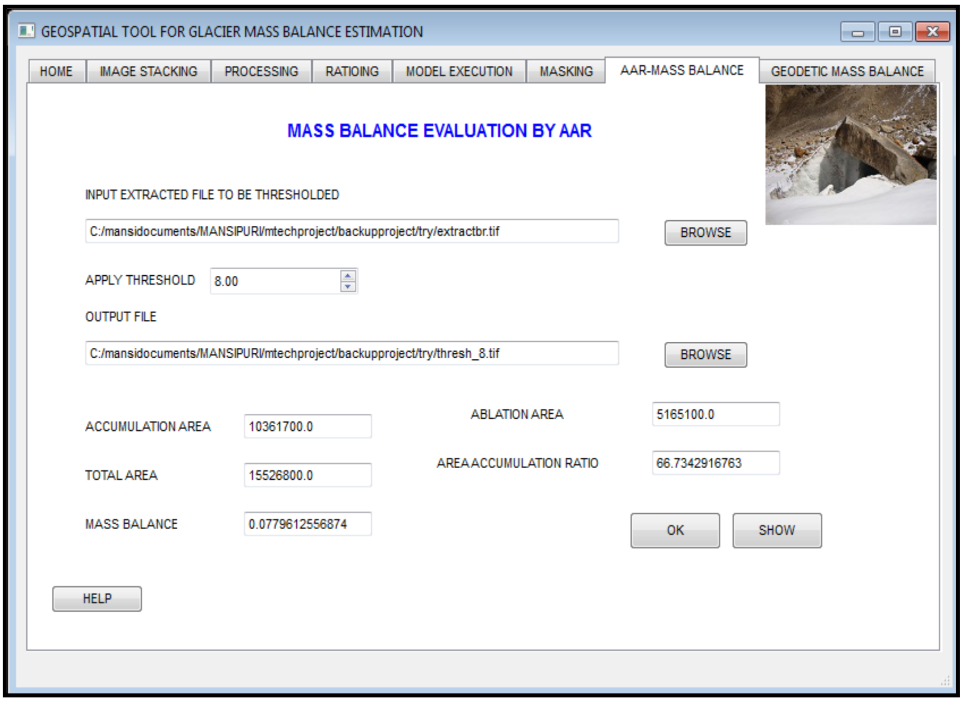


Figure 6.11: *Mass balance Estimation by AAR method*

User should carefully checked the final generated threshold map separating accumulation and ablation area obtained applying threshold and can modify as per actual field scenario.

6.2.7 Mass balance Estimation by Geodetic Method

The figure 6.12 shows the layout of the “Mass Estimation by Geodetic Method.” Input the file for MASTER DEM (previous year DEM) and Input another file for SLAVE DEM (New DEM). Give output file name for DEM difference (Difference in Height). Users also need to give density as well as difference of time between two years. Users also need to give output location of mass balance.

The accuracy of this method is directly proportional to the accuracy of DEM and time of occurrence and it is giving total elevation change which is equated to the meter water equivalent resulting total mass balance. This page has some issues so, this page does not give good result is and not in working condition.

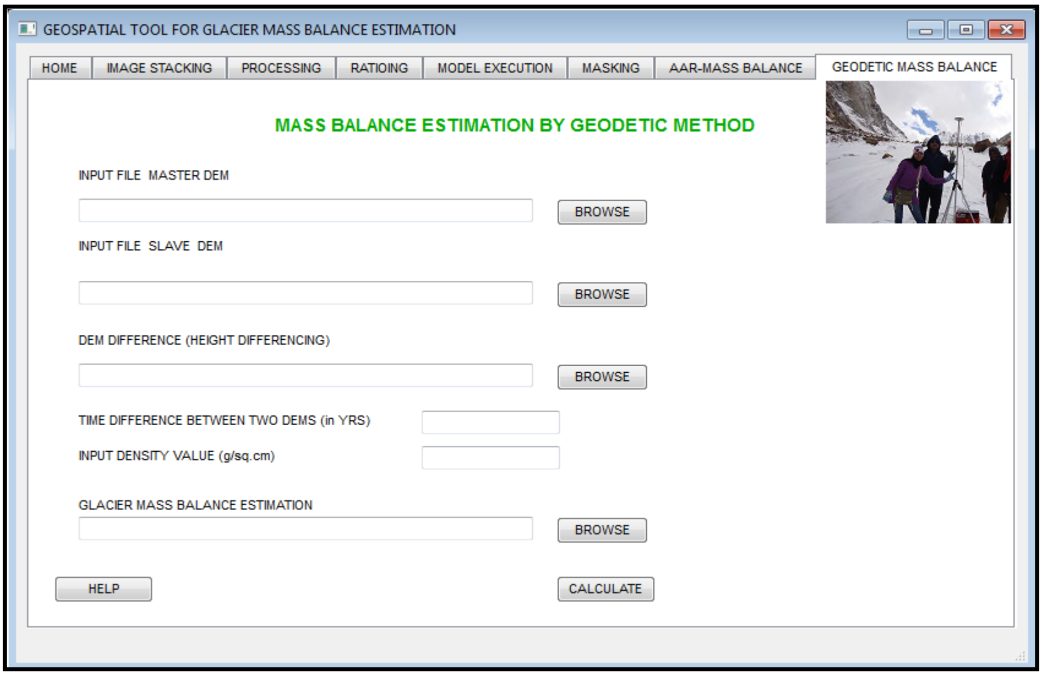


Figure 6.12: *Layout of Mass balance estimation by Geodetic Method*

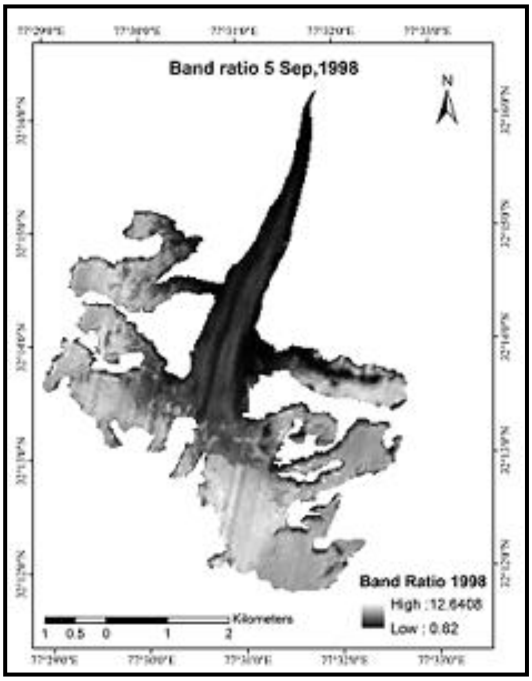
7. RESULTS AND DISCUSSIONS

This study attempts to estimate Glacier Mass balance using Remote Sensing Satellite images by two methods, Accumulation Area Ratio Method and Geodetic Method. This Study involves the establishment of a mathematical model among the actual mass balance, total glacier extent and accumulation area between 2002-2010 in Chhota Shigri Glacier, which results a linear relationship between mass balance and AAR. The linear relation resulted is then further used to estimate mass balance of dataset collected over this period to validate it for Chhota Shigri. Mapping of different zones of glacier is also one of the main objectives of study and primary step for calculating AAR. Glacier is mapped using Band Ratio, NDSI (Optical), Land Surface Temperature, NDSTI (Thermal) and Backscattering coefficients (Microwave).

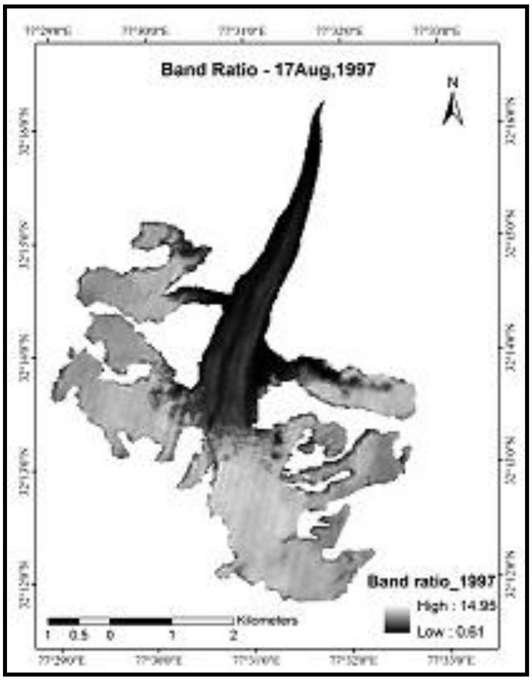
7.1 Time Series for Band Ratio

Band ratio is evaluated for all the Satellite images of 1997, 1998, 2000, 2005, 2006, 2008, 2009, and 2010 and is shown in figure 7.1. Band ratio is the ratio of reflectance of NIR and SWIR bands. The reflectance of these bands is always between 0 & 1, so ratio of these bands results in high values more than 1. The band ratio resulted from different time series images shows very good results in mapping of glacier zones, as it clearly delineates the snow covered area and non snow covered area and help in the determination of snowline and accumulation area. It is proved to be the best index in delineation. Time series of satellite images obtained from different sensors do not show particular range of band ratio value. It is found that this value shows variations from sensor to sensor because of change in reflectance value of sensors. The reflectance of sensor depends on illumination condition which in turn depends on sun elevation angle.

It has been found that in Figure 7.1, Landsat TM (2009, 2010) and Landsat ETM (2000) shows high band ratio value as compared to LISS sensor of IRS because the reflectance value of all the bands of Landsat sensor is higher as compared to other sensors. Figure 7.1 (a) and (b) shows that IRS-1C (1997, 1998) has band ratio values in the range of (0-15) clearly separating the ablation and accumulation zone of the glacier. It also infers that high value of band ratio along with bright region shows accumulation zone while low values and dark region shows ablation zone. And these zones are easily visualized in band ratio images which enhance the contrast of snow covered and non snow covered area.


Band ratio 5 Sep,1998
N
Band Ratio 1998
High : 12.6408
Low : 0.82
Kilometers
1 0.5 0 1 2

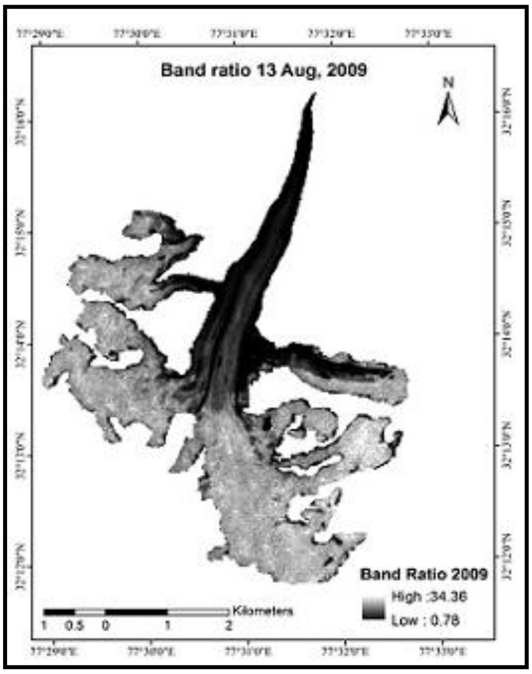
(a)


Band Ratio - 17Aug,1997
N
Band ratio_1997
High : 14.95
Low : 0.61
Kilometers
1 0.5 0 1 2

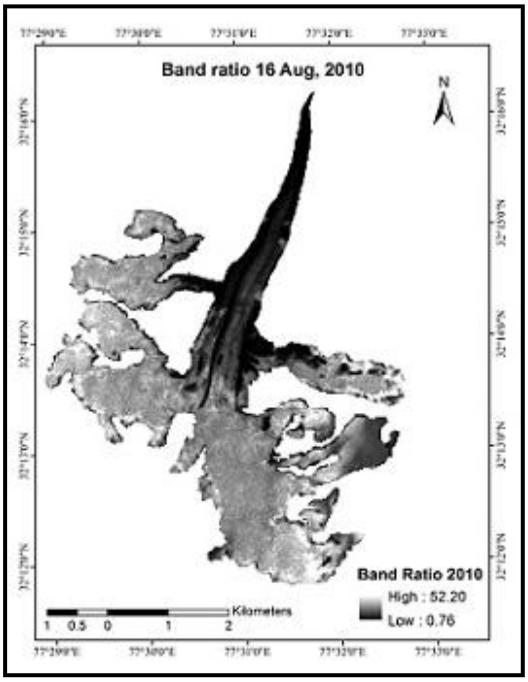
(b)

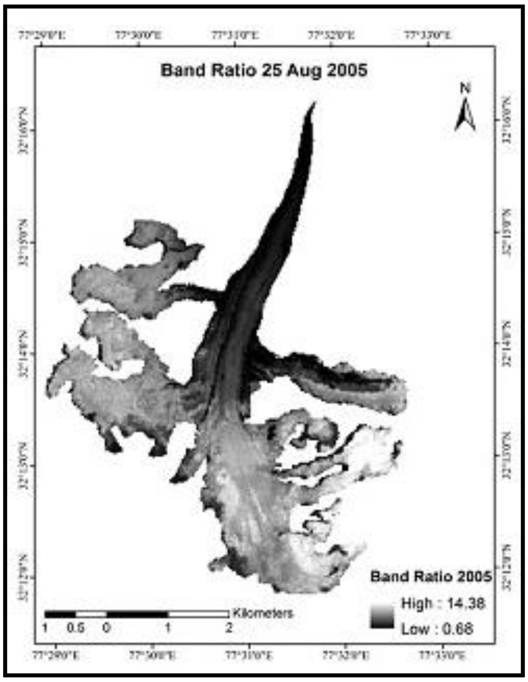

Band ratio 25 Aug,2000
N
Band Ratio 2000
High : 33.62
Low : 0.86
Kilometers
1 0.5 0 1 2

(c)


Band ratio 13 Aug, 2009
N
Band Ratio 2009
High :34.36
Low : 0.78
Kilometers
1 0.5 0 1 2

(d)





(e) *(f)*

Figure 7.1: *Band Ratio calculation for year 1997(a), 1998(b) , 2000(c) ,2005(d), 2009(e), 2010(f)*

The main reason for showing high value in accumulation area which is a snow cover showing high reflectance in VNIR region and low reflectance in SWIR region, resulting very high band ratio values. Whereas, the ablation region has dirty and melted ice containing water on its surface resulting low reflectance in NIR band while rock boulder give high reflectance in this region. In case of SWIR region, melted region show low reflectance because of the absorption due to water and rock boulder again show high values. On ratio of VNIR band with SWIR, melted region and rock boulder show low band ratio and dark region when applied on satellite images. Due to the high change in reflectance values of snow and ice over these two bands, results in image contrast separating accumulation and ablation zone. So application of suitable threshold on the band ratio value proved to be useful to classify whole glacier into accumulation and ablation zone which in turn gives accumulation and ablation area. The threshold range of values for band ratio that can be applied for getting different zone obtained from classified images summarized in table 7.1.

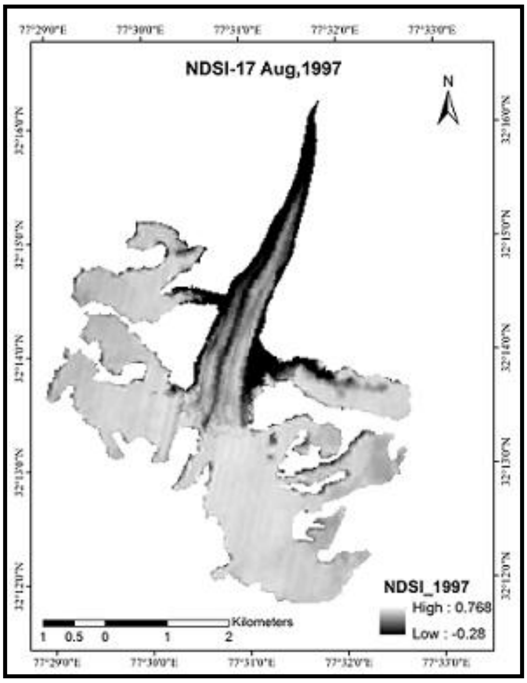
Table 7.1: *Approximate range of threshold for datasets*

Satellite Scene	*Threshold Range for Band Ratio*	*Satellite (Sensor)*
17 August 1997	5.22 - 6.15	IRS-1C (LISS-III)
05 September 1998	5.19 -6.37	IRS-1C (LISS-III)
28 August 2000	12.9-15.4	LANDSAT (ETM)
23 August 2005	5.95-7.07	IRS-P6 (LISS-III)
26 August 2006	5.4-8.8*	IRS-1D (LISS-III)
20 August 2008	0.42-0.60*	IRS-1D (LISS-III)
13 August 2009	0.84-0.94	LANDSAT (TM)
16 August 2010	0.79-0.86	LANDSAT (TM)

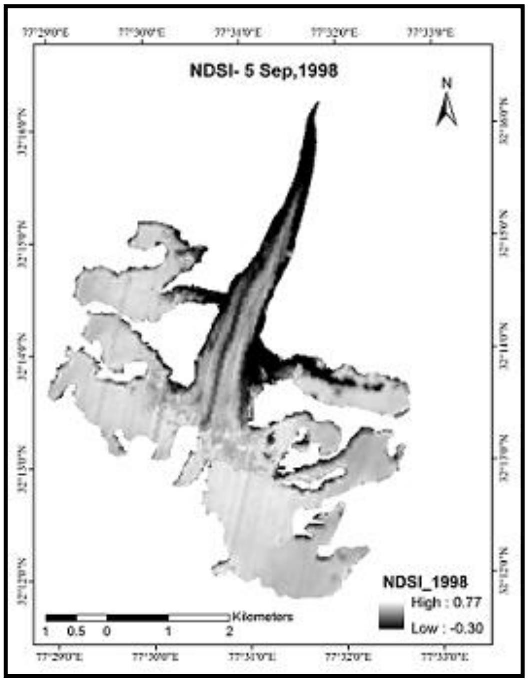
* *Shows that since images have stripping error, So, threshold can vary and even on many area manual digitization can be done considering any other band.*

7.2 TIME SERIES FOR NDSI

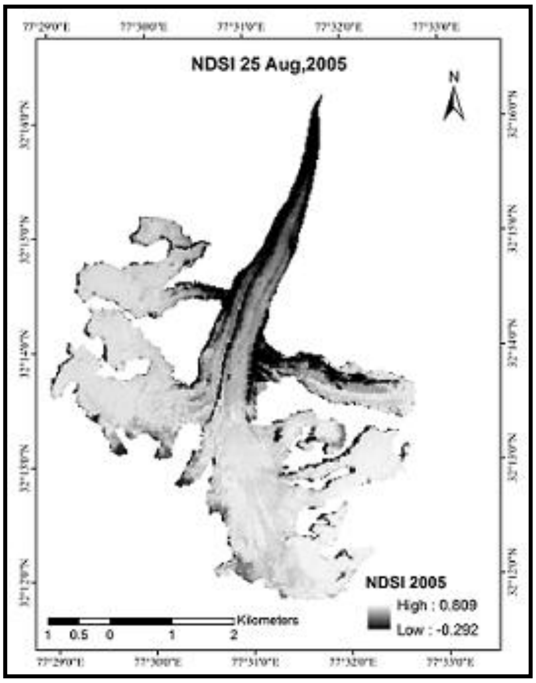
Like band ratio NDSI has also been calculated for different time series. The value of NDSI for all images in between 1 and -1. NDSI is an index which usually differentiates between snow and non snow areas but because of the high reflectance of ice as well as snow, NDSI is not able to differentiate ablation as well as accumulation zone exactly. It mostly includes ablation zone pixels into accumulation zone. Because of this reason, many times manual visual interpretation and digitization has been done for delineating the zone and estimating Glacier Mass balance. Figure 7.2 shows the time series of NDSI.


NDSI-17 Aug,1997
N
NDSI_1997
High : 0.768
Low : -0.28
Kilometers
1 0.5 0 1 2

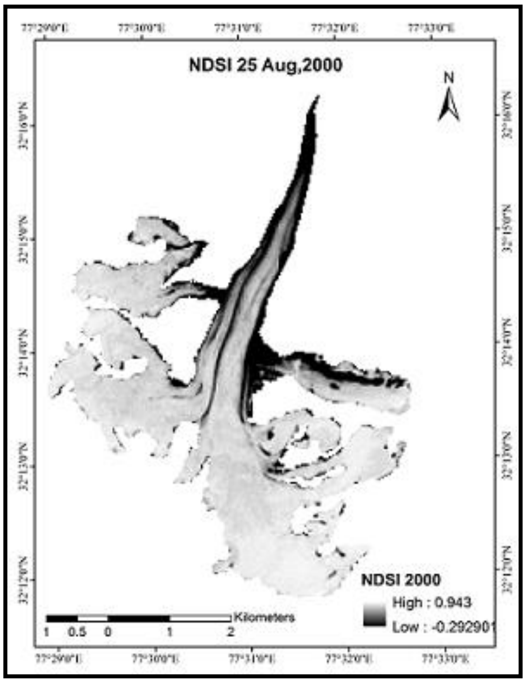
(a)


NDSI- 5 Sep,1998
N
NDSI_1998
High : 0.77
Low : -0.30
Kilometers
1 0.5 0 1 2

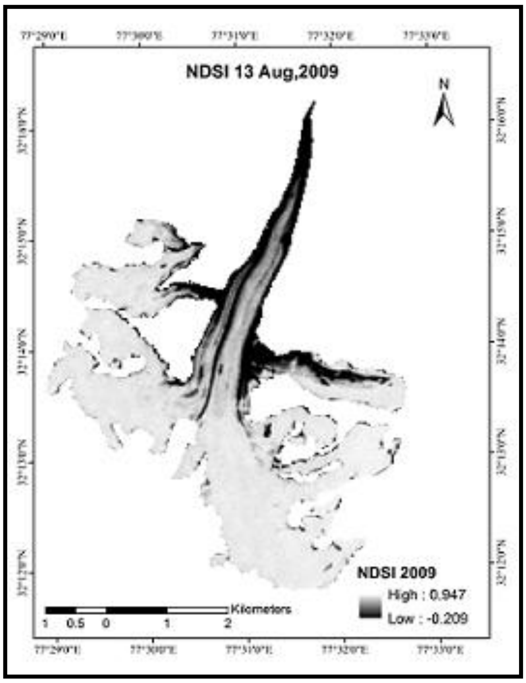
(b)

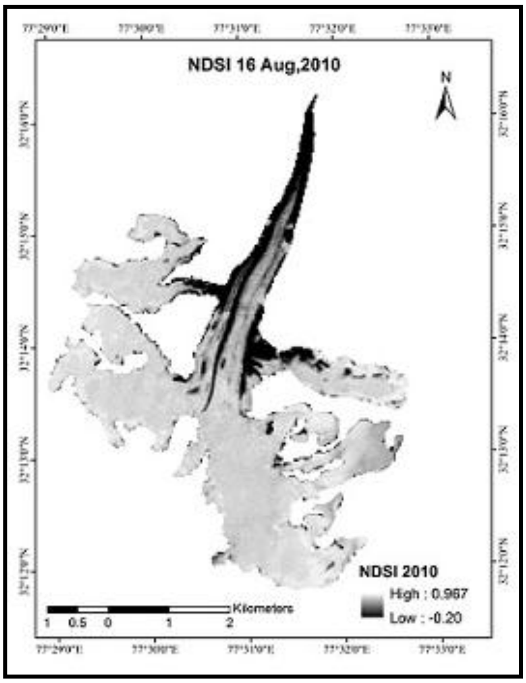

NDSI 25 Aug,2005
N
NDSI 2005
High : 0.809
Low : -0.292
Kilometers
1 0.5 0 1 2

(c)


NDSI 25 Aug,2000
N
NDSI 2000
High : 0.943
Low : -0.292901
Kilometers
1 0.5 0 1 2

(d)





(e) ***(f)***

Figure 7.2: *NDSI calculation for year 1997(a), 1998(b), 2000(c), 2005(d), 2009(e), 2010(f)*

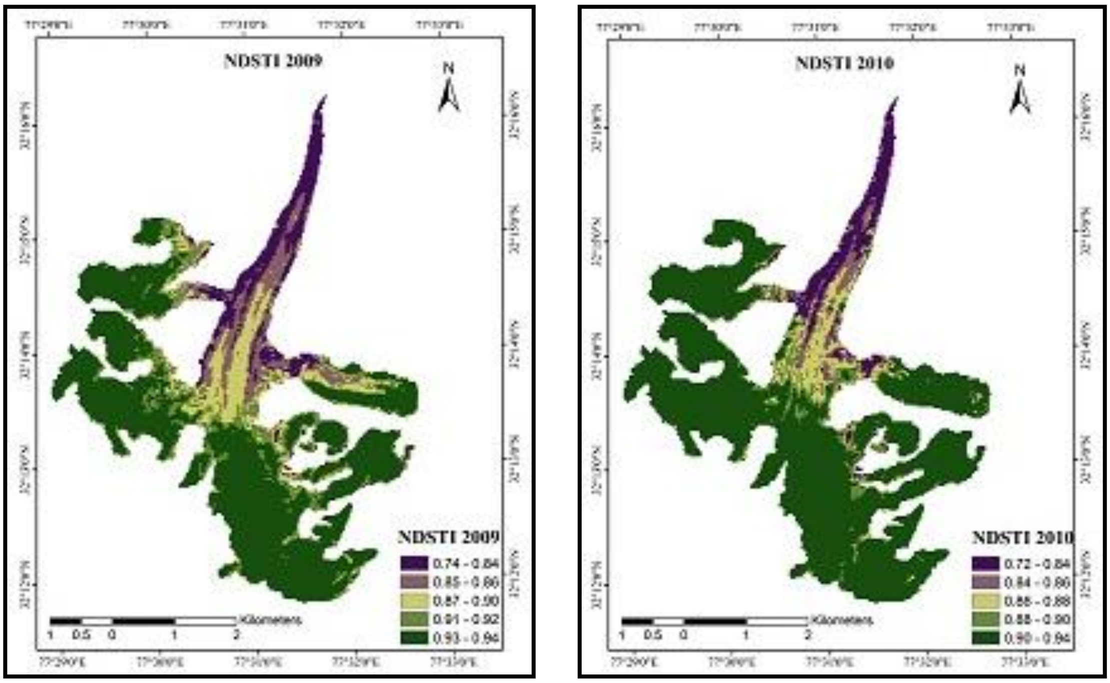
The results obtained from NDSI for time series are shown in Figure7.2 which depicts that NDSI is not able to delineate snow and non snow (ice+ water) areas. Images suggest that this index either overestimate the delineation of zone of glacier as seen in 2010 or underestimate the snow covered area as shown in 1997. In both case the only solution is to threshold the NDSI with some set of value and based on visually interpretation of FCC and band ratio image, area of accumulation or ablation is evaluated finally from NDSI which can either increased or decreased. The value range for applying threshold has been provided in Table 7.2

Table 7.2: *Approximate range of threshold for NDSI datasets*

Satellite Scene	***Threshold Range for Band Ratio***	***Satellite (Sensor)***
17 August 1997	5.22 - 6.15	IRS-1C (LISS-III)
05 September 1998	5.19 -6.37	IRS-1C (LISS-III)
28 August 2000	12.9-15.4	LANDSAT (ETM)
23 August 2005	5.95-7.07	IRS-P6 (LISS-III)
26 August 2006	5.4-8.8*	IRS-1D (LISS-III)
20 August 2008	0.42-0.60*	IRS-1D (LISS-III)
13 August 2009	0.84-0.94	LANDSAT (TM)
16 August 2010	0.79-0.86	LANDSAT (TM)

7.3 Time Series for NDSTI

Accumulation and ablation zone of glaciers are also delineated using NDSTI ratio for 2000, 2009 and 2010. The time series of NDSTI are shown below: since it is also normalized difference so the value ranges between 0 and 1. The index shows very high value for whole region. This index works on radiance image of band 1 and band6 showing better result. It is based on the high reflection of snow/ice in the band 1 and high absorption in band 6. Since this index is well suitable for the delineation of accumulation and ablation zone based on pixel to pixel matching. It does not mix water bodies' pixel with snow/ ice areas.

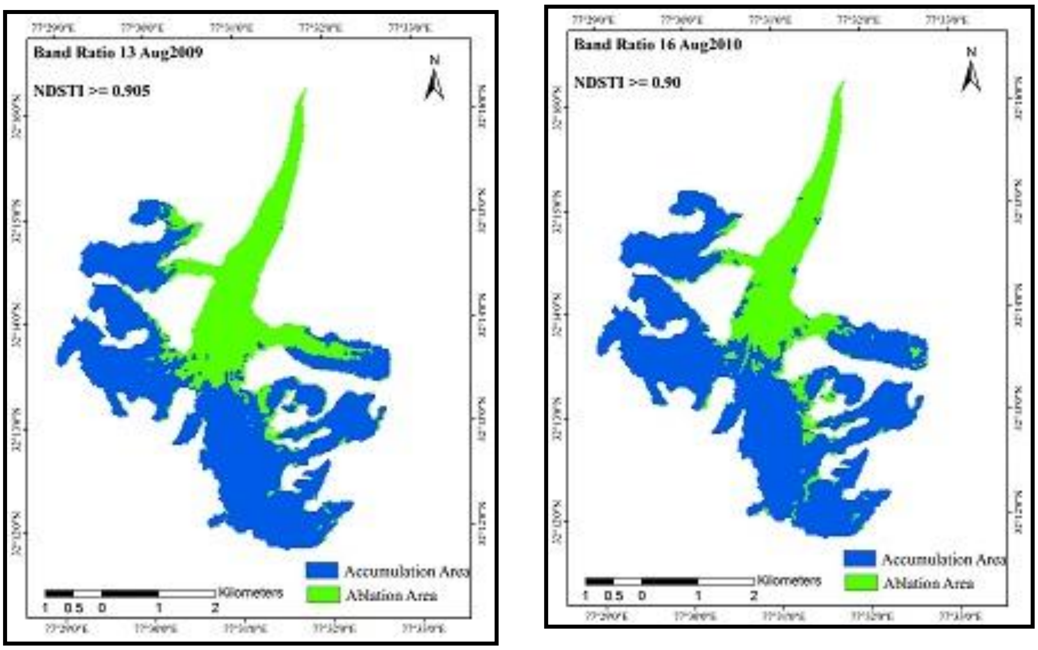


(a) *(b)*

Figure 7.3: *NDSTI calculation for year 2009 (a), 2010(b)*

On visual interpretation with satellite image in the figure7.3 (a) and (b), it has been found that dark green area corresponds to snow, while light colour corresponds to ablation area while purple colour shows rock boulders, moraines on the side edges of the glacier. The value of NDSTI range is from 0.7 to 0.95. It has been found that on threshold > = 0.9, NDSTI delineate the accumulation (snow covered) and ablation (non snow area)

On comparison with NDSI of the same year images, it has been found that NDSI mixes the snow pixel with the neighbouring pixel at the Snow line area and overestimate the zone. On considering performance of both NDSI and NDSTI on visual interpretation, NDSTI prove to be better among two indexes. The threshold value and result obtained from NDSTI for year 2009 and 2010 on applying thresholds 0.905 and 0.9 has been shown in figure 7.4.

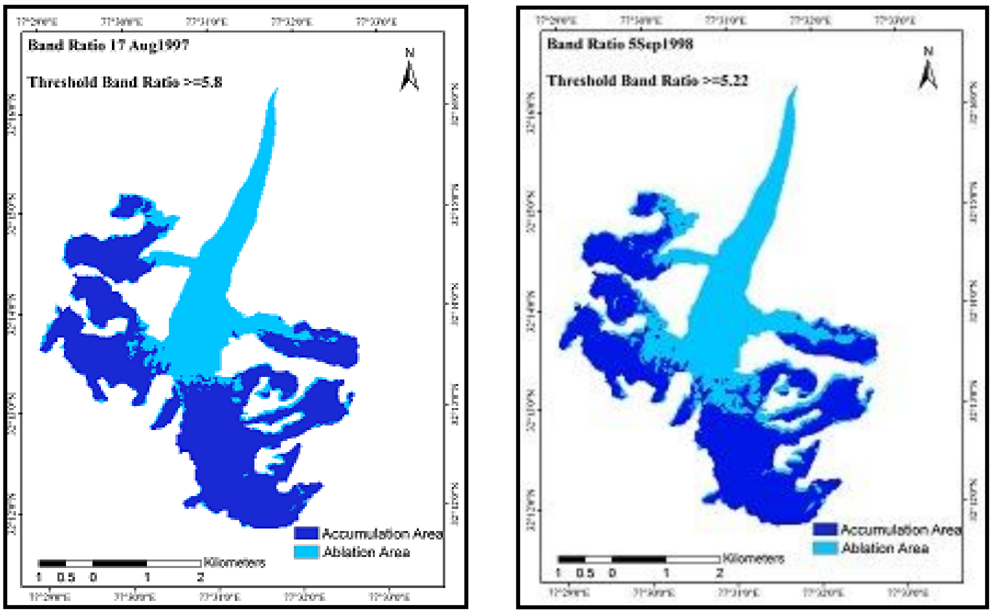


(a) *(b)*

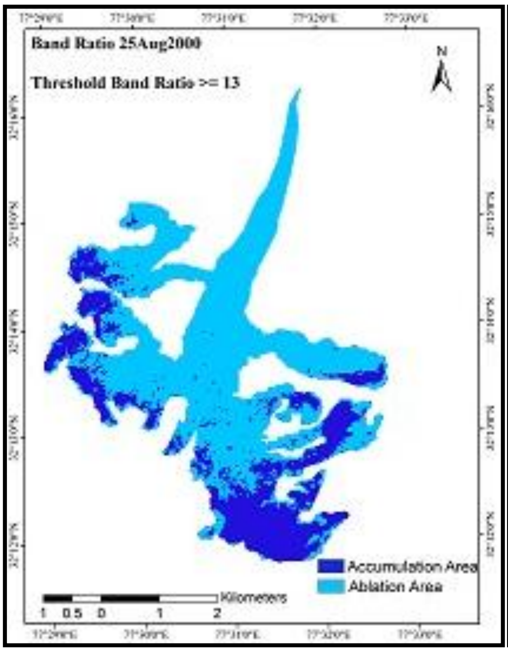
Figure 7.4: Threshold applied on NDSTI separating zones of glacier

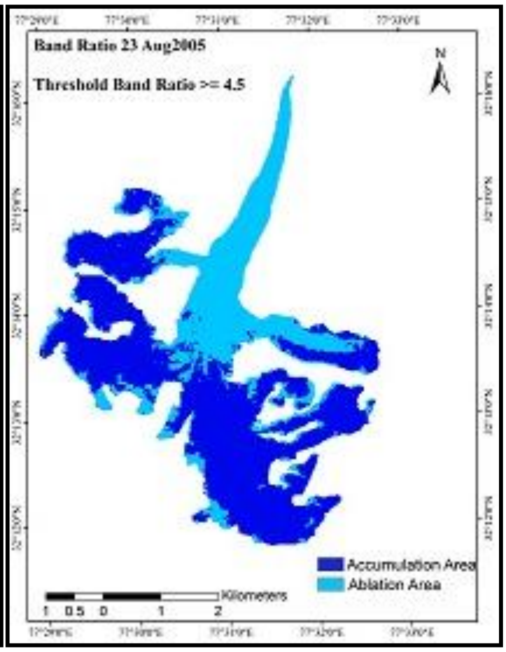
7.4 Threshold on Band Ratio and NDSI

On applying several thresholds within the range given in table 7.1 and table 7.2, zones of glaciers get separated. It has been found that the best matched threshold that mapped glacier zones has been shown in all the images of figure 7.5. It has been inferred that the threshold range varies with sensor and hence the band ratio value too. For IRS sensor, the value of threshold range from 4 to 6, while in Landsat the value ranges from 8 to 13.

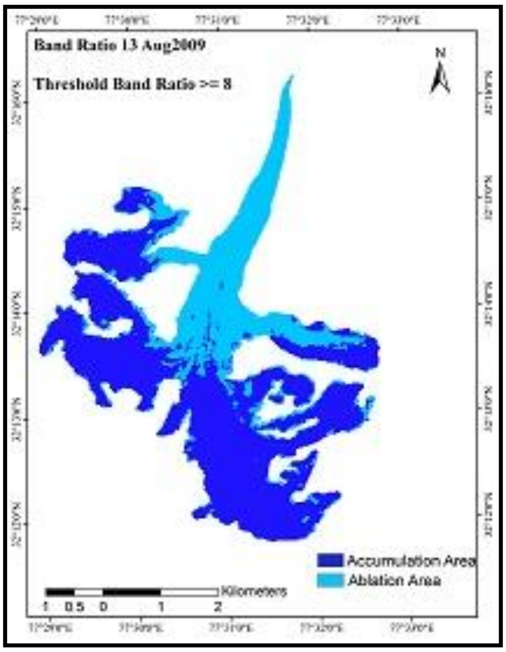


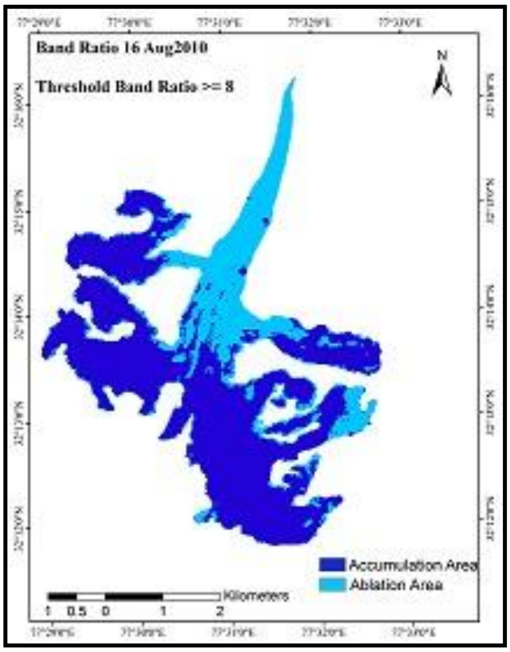
(a) ***(b)***





(c) ***(d)***





(e) ***(f)***

Figure 7.5: *Threshold apply to Band Ratio separating zones 1997 (a), 1998 (b), 2000(c), 2005(d), 2009(e), 2010 (f)*

All the images in figure 7.5 are threshold by appropriate threshold to get the accumulation and ablation zones. The results obtained match with the actual FCC and with other band combinations. But after applying threshold sometimes, there is need of doing manual digitisation as NDSI or band ratio either overestimate or underestimate the superimposed area between accumulation and ablation zone due to cloud cover and shadow effect.

To visual discriminate snow from cloud band combination of 7, 5 and 3 in case of Landsat TM and ETM can be used which shows the exact location of cloud in the satellite images. In case of IRS sensor FCC 4, 3, 2 can easily differentiate snow and cloud as cloud shows bright white patches over the images and snow can be viewed as cyan colour, makes us visually aware of above said two features.

7.5 Results from Land Surface Temperature

Land surface temperature evaluated through Single Channel Algorithm for thermal band of Landsat TM for year 2009 and 2010. The main parameters used in this study are emissivity and water vapour content. Since usually scientist take emissivity over the glacier usually 0.97-0.99. Rees (1990) give the average emissivity of some of object at 10µm.

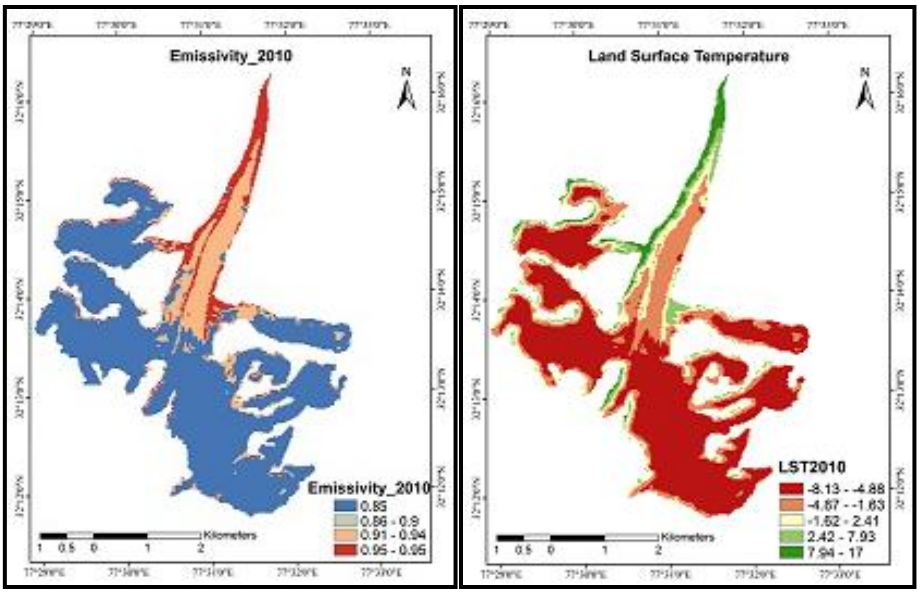
Table7.3: *Emissivity for various objects at 10µm (source: Rees, 1990)*

Objects	***Emissivity***
Soil(moist)	0.94 -0.95
Glacier	0.85
Compressed (snow)	0.70-0.85
Ice	0.98
Snow	0.97-1.0

But as it depends upon the field visit and the morphology of glacier based on literature review. Emissivity of Chhota Shigri glacier is divided into 3 parts and classified as in figure 7.6 (a).

1. Soil moist whose emissivity chosen to be 0.95
2. Dirty ice, since it contains water too so emissivity chosen to be 0.9.
3. Snow Compressed (accumulation zone) chosen to be 0.85.

Based on the criteria the emissivity map and Land surface Temperature of 2010 is shown in figure 7.6.



(a) **(b)**

Figure 7.6: *Classified Emissivity for 2010 (a) and Land Surface Temperature for 2010 showing clear difference between snow covered area and non snow covered area. (b)*

Figure7.6 (b) resulted in land surface temperature of 2010 shows the variation in temperature differentiating accumulation zone (snow covered region) from ablation zone. The accumulation zone of glacier shows very low temperature of around -8°C. While table 3.2 also validates the fact that the lowest temperature at 4920m in 2009 is found to be -13.2° C and this elevation in 2009 comes under accumulation zone. While side moraines and rock boulder and debris shows high temperature i.e. more than 2.4 °C and increase up to 17° C. Melting snow shows temperature variation of -4.67 to 2.41. These variations come from the fact that liquid water is found to be warmer than snow. So, presence of liquid water on the ice surface causes temperature to rise as compared to snow accumulated area makes the wet zones are detectable in thermal remote sensing. So, in the above figure 7.6 (b) temperature results in separation of the accumulation and ablation zones.

7.6 Results from RISAT-1

Zonation of glacier is also done on RISAT-1 image collected on 8 Aug 2012 based on their backscattering coefficients. The values of backscattered coefficients for main glacier range from -32 to 4 dB. Since the problem of layover and foreshortening is there, still the main glacier is visually differentiated into accumulation and ablation zone. Image shows basically high and low backscattered area. As per the fact, dry snow always show low backscattered due to smooth surface and low dielectric constant (snow usually have 3.2, (Pellika and Rees, 2010)) and absence of melt event. The grain size of this region is also small which causes low surface scattering. The backscattered value for accumulation zone in figure 7.7 is nearly within the range of -14dB to -22dB. While the ablation zone have backscattered values ranging from -14dB to 4dB. Ablation zone in radar image is known as wet snow or bare ice radar zone. This region as seen in the image show high backscattering due to high dielectric constant of water present over the surface, since another factor that causes high backscattering is surface roughness which influences the microwave signal with reflection and surface layer with volume scattering. The grain size of this region is also found to be large and shows high back scattered values.

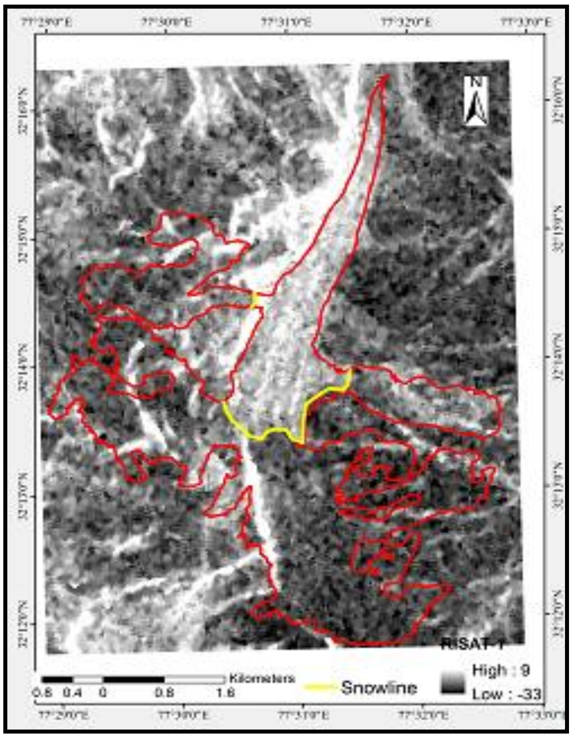
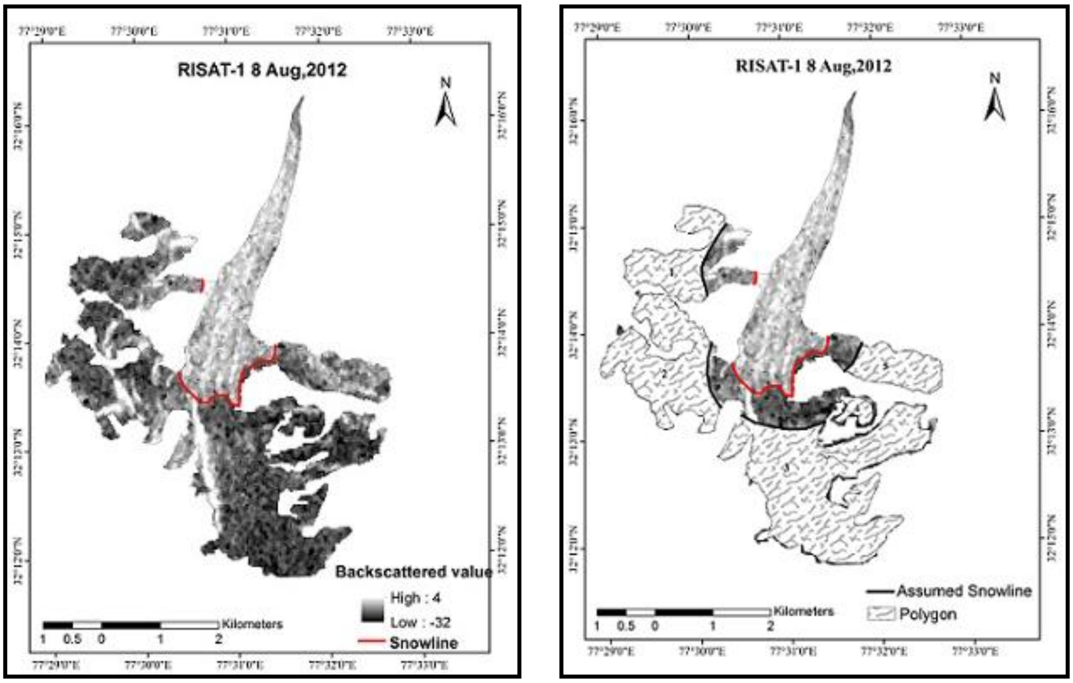


Figure 7.7: *Risat-1 Image dated 8 Aug 2012, overlayed by boundary shapefile*



(a) *(b)*

Figure7.8: *Risat-1 of Chhota Shigri clears Depicting Glacier zones with their Backscatterd value (a) Assumed Snowline and Digitised Polygon for approximate Mass balance (b).*

Here snow metamorphism makes the snow grain size large contributing to high backscattering value. The snowline between the accumulation and ablation zone has been drawn considering SRTM DEM and it is found to be around 4810mts. The RISAT-1 image of 8Aug 2012 has been shown in figure 7.8 (a). Since the image is of 8 Aug 2012 which is ablation period and study deal with the annual mass balance during end of ablation period , so assuming that during the end of August the SLA is shifted from 4810 (Red line) to 4950 (black line). The mass balance is estimated by digitizing the polygon below the snowline. The table 7.4 gives the area of digitized polygon.

Table 7.4: *Area of polygons digitised on RISAT image by assuming Snowline*

Polygon Number	***Area (in Km^2)***
1.	1276261.567
2.	2513144.69
3+4	4968958.413
5	916594.6267

Total	9674959.29

Total area of glacier = 15.52km^2

AAR = 9.67/15.52 = 0.6230

But, in percentage it is 62.30

Annual Mass Balance for 2011-12 = 0.0386 * 62.30-2.5007 = -0.09519 m w.e

7.7 Estimation of Snow Line Altitude

Snow line Altitude is considered to be one of the necessary components for estimating mass balance. It is basically elevation above which there is accumulation zone and below which there is ablation zone. SLA for all the time series is digitized and estimated by taking average of point values covering the line. The reason for doing this is because snowline does not have same value at every point. The value for time series has been calculated as in table 7.5

Table7.5: *SLA Values for time series of Satellite images*

YEAR	*ELEVATION*
1997	4882 ± 70
1998	4888± 14
2000	5012 ± 52
2005	4822 ± 27
2006	5023 ± 29
2008	5000 ± 40
2009	4801 ± 25
2010	4783 ± 43

7.8 Results from Mass Balance Estimation by AAR Method

After applying required threshold on the Band Ratio and NDSI, there is need to do manual digitization on some of the images due to presence of shadow, cloud cover and due to sensor saturation. Manual digitization can be done by visual interpretation, by the knowledge of study area and by the use of ancillary information. In case if some area of glacier is covered with shadow or cloud cover in one of the satellite images while all the rest images shows snow accumulation in that that region and moreover that region is at high elevation then this part is considered for digitization. Once accumulation and ablation zones of glacier get separated, the next step is the calculation of mass balance. Accumulation area of the glacier is calculated through accumulation zone. As we know that the area of glacier is around 15.52 km^2 and accumulation area is known, so AAR is easily calculated. Once AAR for the time series is calculated, mass balance is estimated using equation 7.1.

Annual Mass balance = 0.0386 * AAR – 2.5007…………………………. (7.1)

This regression model analysis validates the AAR and mass balance over Chhota Shigri glacier. The accumulation and ablation areas obtained from the mapping of satellite images using two different techniques of NDSI and BAND RATIO are approximately equal as that obtained from ground investigation. AAR also ranges from nearly 29 to 72 which are also relatively similar to data obtained from the field given in table 5.2. The mass balance evaluated from this method is comparable and shows good correlation with the mass balance calculated on the ground. The mass balance of 1997, 2005, 2009 and 2010 showing positive mass balance while 1998, 2000, 2006, 2008 showing a negative mass balance thus shows good result of using this mathematical model. Mass Balance Estimated through band ratio and NDSI by calculating AAR using Accumulation area have been shown in Table 7.6 and 7.7. These tables show time series of accumulation area, ablation area, specific threshold applied, AAR calculation resulting in mass balance calculation.

Table 7.6: *Mass balance calculated through the AAR method by applying a suitable threshold on the Band Ratio separating Accumulation and Ablation Areas*

Date of scene	*Threshold (Band Ratio)*	*Accumulation Area*	*Ablation Area*	*AAR (%)*	*Mass Calculated (m.w.e.)*	*Mass Observed (m.w.e.)*	*Remarks*
17Aug1997	5.8	10.15	5.38	65.39	0.0233	Nil	Positive
05Sep1998	5.2	8.64	6.88	55.67	-0.35	Nil	Negative
28Aug2000	13.0	4.60	10.92	29.63	-1.35	Nil	Negative
23Aug2005	4.5	10.48	5.04	67.52	0.105	0.1	Positive
26 Aug2006	5.66	4.40	11.12	28.35	-1.42	-1.4	Negative
20Aug2008	8.0	6.59	8.93	42.42	-0.863	-0.93	Negative

13Aug2009	8.0	10.36	5.16	66.75	0.077	0.13	Positive
16Aug2010	8.0	11.19	4.33	72.10	0.282	0.33	Positive
8Aug2012*	-	9.67	5.82	62.30	-0.095	-	Negative
16Aug2010**	-0.43	10.35	5.12	66.67	0.08	0.33	Positive

*SAR **LST

So, it has been deduced from table 7.6 that applying AAR method on microwave removes our dependency over cloud covered optical data. On applying appropriate threshold over this accumulation area can be estimated and using regression model Mass balance can be estimated.

Table 7.7: *Mass balance calculated through the AAR method by applying a suitable threshold on the NDSI separating Accumulation and Ablation Areas*

Date of scene	***Threshold (NDSI)***	***Accumulation Area***	***Ablation Area***	***AAR (%)***	***Mass Calculated (m.w.e.)***	***Mass Observed (m.w.e.)***	***Remarks***
17Aug1997	0.57	10.16	5.36	65.43	0.024	Nil	Positive
05Sep1998	0.61	8.60	6.92	55.40	-0.36	Nil	Negative
28Aug2000	0.84	4.65	10.87	29.9	-1.34	Nil	Negative
23Aug2005	0.6	10.45	5.07	67.33	0.098	0.1	Positive
26Aug2006	0.4	4.38	11.14	28.22	-1.41	-1.4	Negative
20Aug2008	0.41	6.60	8.94	42.52	-0.86	-0.93	Negative
13Aug2009	0.78	10.40	5.12	67	0.085	0.13	Positive
16Aug2010	0.80	11.10	4.42	71.51	0.259	0.33	Positive

The table 7.6 and 7.7 shown above are obtained from two mapping techniques NDSI and band ratio. The threshold values of NDSI for separating accumulation and ablation zones are in the range of 0.4 to 0.8 and for band ratio, though the sensors are different and their reflectance is also different so, range is variable. Mass balance is calculated at the end of ablation season, so there is difficulty in collecting cloud free and shadow free images. As per the results year 2006 shows highest glacier mass balance loss of -1.41 m w.e. While studies depict glacier gain of mass balance in 2010 is 0.28 m w.e.

For 1997, the threshold which is best suited for the zonation of accumulation and ablation region is 5.8 in case of band ratio which results accumulation area of 10.15km^2. The reason for having positive mass balance of 1997 is true because as in table 7.5., the SLA line is found close to 2005 and 2009 which too shows positive mass balance. Since manual digitisation on some part of the image need to be done in case of NDSI due to mixing of pixels of accumulation and ablation zone. The resulting area comes to be around 10.16 km^2 shows AAR of around 65.4% found nearly to AAR calculated around 67 and 66 for 2005 and 2009. The mass balance value for 1997 is found to be 0.023 m.w.e, i.e. very near to SLA at equilibrium position (ELA). At the end of ablation region estimating SLA is equal to ELA for annual mass balance, but during time series analysis, ELA is that altitude value where mass balance is found to be zero.

For the image of 5 September1998, the mass balance found to be negative as SLA is found to be higher than 17 August 1997, which is nearly found to be in equilibrium. The AAR ratio for 1998 image is around 55%, showing mass balance of -0.35 m.w.e. Deducing the fact that for the equilibrium line altitude AAR value should be between 65% and 55%.

The year 2000, 2006 and 2008 have mostly same mass balance in the same range. Even 2000 and 2006 show very close mass balance of -1.35-1.36 m.w.e and 1.41-1.42 m.w.e. respectively because of the low SLA.

It has been analysed through the table 7.6 and table 7.7 that for some years, mass balance deviation is more, because of the absence of particular time period of estimating mass balance. i.e. difference in the time period of estimating mass balance in field and as well of satellite image. Deviation in the accumulation area and ablation area calculated by NDSI and band ratio technique is due to errors in manual digitisation or by false interpretation of pixel due to cloud cover and shadow. These techniques give correct remarks on the positive or negative mass balance. The accuracy of the mass balance depends on cloud free and shadow free image. Moreover, timely acquisition of the satellite imagery is another paradigm.

As per statistical analysis concerned, the regression mathematical model gives coefficient of correlation nearly equal to 0.95, and mass balance calculated through that regression give mass balance nearly close to the actual ground based mass balance. The RMSE error calculated for each year for both techniques.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(X_{obs,i} - X_{model,i})^2}{n}}$$

The RMSE error calculated for NDSI and Band Ratio is as 0.049 and 0.044 respectively which is admissible. The average mass balance so calculated from 2005 to 2010 for ground data is -0.354m.w.e. while it is around -0.3656m.w.e for NDSI and -0.3638m.w.e for band ratio. The average percentage difference between actual and observed data is 11% in case of band ratio and nearly 14% in case of NDSI which is slightly more.

Deviation of actual mass balance (field data) from the regression model estimated using ground based AAR value is mentioned into table 7.8. The percentage difference in the deviation of mass balance comes to be -13%.

Table 7.8: *Deviation of Actual mass balance and that of derived from regression equation with actual AAR values*

YEAR	*AAR*	*Mass Balance (observed in m w.e)*	*Mass Balance (calculated in m w.e) using eq 7.1*
2003	31	-1.4	-1.3041
2004	31	-1.2	-1.3041
2005	74	0.1	0.3557
2006	29	-1.4	-1.3813
2007	36	-1.3	-1.1111
2008	37	-0.93	-1.0725
2009	63	1.3	-0.0689

Kulkarni (1992) has described the AAR approach in details in paper "Mass balance of Himalayan glaciers using AAR and ELA methods". He used field data related to mass balance, equilibrium line, accumulation area and ablation area for Tipra Bank, Gara, Gor-Garang and Neh-Nar Glaciers to derive the following equation for the calculation of specific mass balance for the Western Himalayan Glaciers of India. Kulkarni et.al (2004) used this equation for monitoring the glacial mass in the Baspa basin, Himachal Pradesh as:

$$Y=243.01*X-120.187 \quad (7.2)$$

Where Y is specific mass balance in water equivalent (cm.) and X is Area Accumulation Ratio (AAR).

On using this equation, the mass balance calculated and it comparison with actual and regression model derived mass balance has been mentioned in table 7.9.

Table 7.9: *Comparison of mass balance calculated through eq 7.2 using derived AAR from Band Ratio with actual and mathematical model derived mass balance*

Date of scene	*AAR (bandratio)*	*Mass balance calculated through eq.7.2 (in m.w.e)*	*Mass Balance (observed in m w.e)*	*Mass Balance (calculated by eq7.1 in mw.e)*
17Aug1997	0.65	0.387172	nil	0.0233
05Sep1998	0.55	0.150967	nil	-0.35
25Aug2000	0.29	-0.48183	nil	-1.35
25Aug2005	0.67	0.438934	0.1	0.105
18Aug2006	0.28	-0.51294	-1.4	-1.42
20Aug2008	0.42	-0.17102	-0.93	-0.863
13Aug2009	0.66	0.420222	1.3	0.077
16Aug2010	0.72	0.550232	0.33	0.282

The mass balance evaluated through equation shows wide variation from the model derived and actual mass balance from field data. Since this equation is usually used for estimation of mass balance of glacier of Western Himalayas. Mass balance derived from the equation over whole Western Himalaya's shows large difference and deviation causing average difference of -0.22m.w.e and -5.3m w.e in case of mass balance derived from actual field and equation over Chhota Shigri glacier. While the RMSE error found to be 0.66 and 0.58 as in case of actual and observed over Chhota Shigri which is not acceptable causing much deviation than the real scenario. But due to such variation it is found disadvantages to use such equation globally. So, it is advisable to develop model for each glacier based on the ground data or other concerned parameters to estimate glacier mass balance based on local regime rather than global so as to increase the accuracy in such kind of estimations.

7.9 Estimation of Geodetic Mass Balance

The Master DEM for calculation of Mass balance over Chhota Shigri glacier is derived from the Contour map of 40 meters interval derived from base map of 1966 found in between elevation of 4103 to 6171m and resample at 30 m. The Master DEM used for study has been shown in figure 7.9.

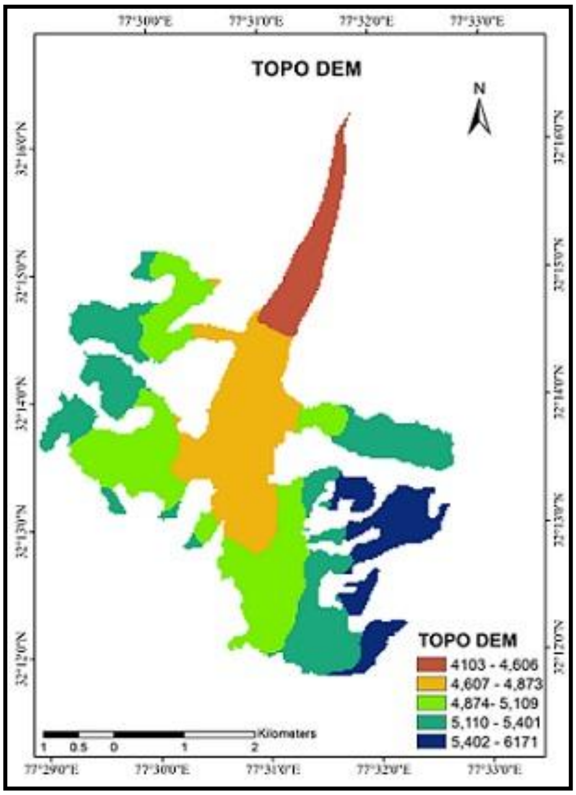


Figure7.9: *DEM Generated through contour interval of 40 metres have 30 meter resolution*

The Slave DEM has been taken as SRTM DEM having 90 meter resolution resampled at 30 metres. SRTM used is of Feb, 2002, so there is effect of SAR penetration into ice also, without considering penetration, the elevation of SRTM found to be around 4098 to5777m. The SRTM DEM (Slave DEM) with its elevation range has been shown in figure 7.10.

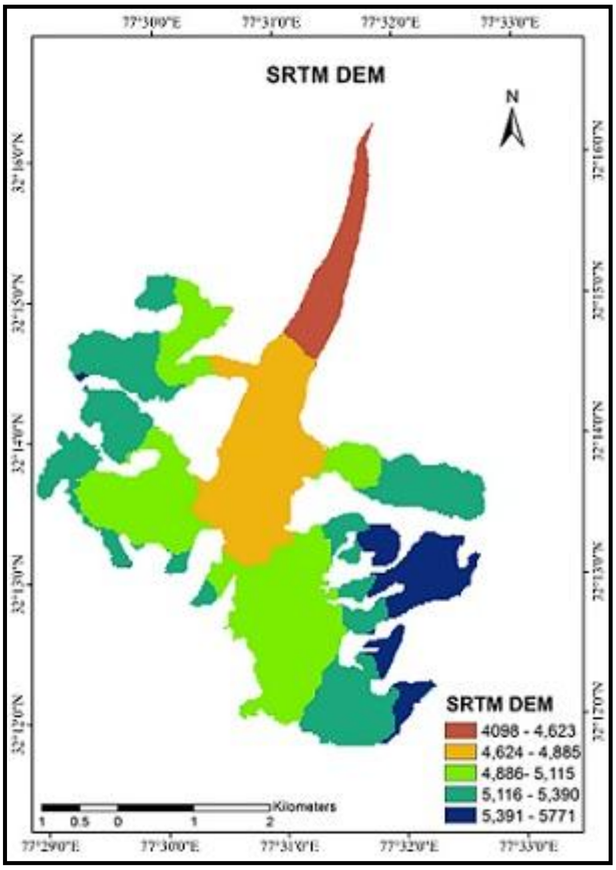
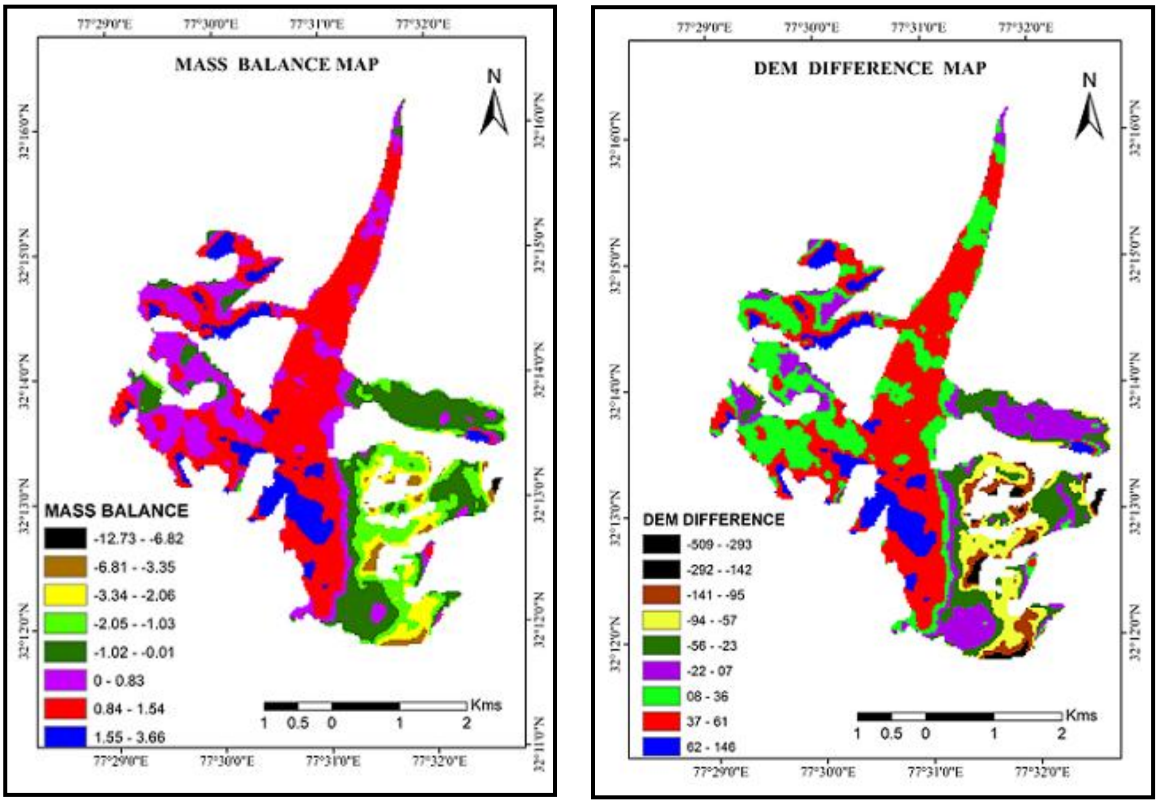


***Figure 7.10**: showing the SRTM DEM taken from USGS for Feb 2002*

The accuracy of geodetic method is generally based on the accuracy of DEM used. On comparing TOPO DEM and SRTM DEM classified map it is found that the Class by Class there is not much difference between the two DEMs that occur over 36 years. In order to calculate mass balance difference of two DEM, height difference map is generated by subtracting SRTM DEM from TOPO DEM. So, if elevation comes to be positive then it results in increase in elevation at that particular pixel over 36 years while, negative sign shows decrease in height due to calving, melting, decomposition etc. Height difference map is directly converted into water equivalent if multiplied with density assuming it to be constant over whole glacier i.e. 900kg/m^3. The height difference and mass balance (in meter water equivalent) has been evaluated and displayed in figure 7.11 (a) as DEM difference map, while figure 7.12(a) shows Mass balance (in m w.e.)

From the DEM difference map it has been seen that along the main, east, south east trunk of glacier there is increase of around 8 to 61 m of elevation during these 36 years (1966-2002). This increase in elevation is mainly due to accumulation of snow, avalanche etc for which the surface of glacier can give positive value for longer period. Whereas, in the west tributary, glacier shows decrease in elevation -94 to -07m. The reason of such kind of decrease is the slope of terrain. On looking slope it is justified that this part of glacier have slope more than 22° which cause less accumulation. Due to high slope, erosion of surface material is more as compared to main glacier. It has been seen that the pixel (black pixel) shows high decrease in elevation due to presence of deep depression.



(a) ***(b)***

Figure 7.11: *Dem Difference (Height) Map derived (a) and Mass balance estimated by Geodetic Method (b)*

Whereas same kind of pattern has been seen in Mass balance Map averaged over 36 years which results in annual mass balance. Since it shows mass balance for 1 year, so mean comes to be around 0.24 which shows overall positive mass balance according to the trend of last 36 years. The positive mass balance has been observed will be in the range of 0.84m w.e. to 1.54m w.e. which can be considered an appreciable change over 1 year because slope is found to be gentle ranging between 0° to 10°. Even east flank of glacier also observed positive mass balance but change is very less because some part of the terrain has high slope. The west tributary glacier shows negative mass balance between -0.01 to -3.34m.w.e. which is found to be very high. As of now, positive annual mass balance is found to be 0.33m.w.e and negative mass balance is around -1.4m.

But as per latest studies , the Chhota Shigri glacier experience negative mass balance during over last 22 years i.e 1988 -2010 causing loss in mass balance -3.8 ± 2.0m w.e. corresponding an annual increase of -0.17± 0.09 m w.e.yr^{-1}. While using Geodetic method Using SPOT DEM results in the mass balance from 1999-2010 is -4.8±1.8m w.e. corresponding annual increase of -0.44±0.16m w.e.yr^{-1}. From this point conclusion comes out to be there over 1988-1999, the glacier experience positive mass balance of 1.0± 2.7m w.e. causing annual increase of 0.09±0.024m w.e.yr^{-1}. (Vincent *et al*., 2013).

In the current study, mass balance is estimated over 36 years i.e from 1966-2002. Considering the fact that over 1988-1999, increase in Glacier mass balance is observed i.e 0.09±0.024m w.e.yr^{-1}. So assuming the same for 33 years from 1966-1999 mass balance comes to be positive 3.97± .792m w.e. and remaining three years, assuming -0.44±0.16m w.e.yr^{-1}, it comes out to be -1.32±0.48m. So, the overall mass balance over 1966-2002 is nearly positive and comes to be 2.74±0.312. m w.e. corresponding an annual increase of 0.076±0.0086m w.e.

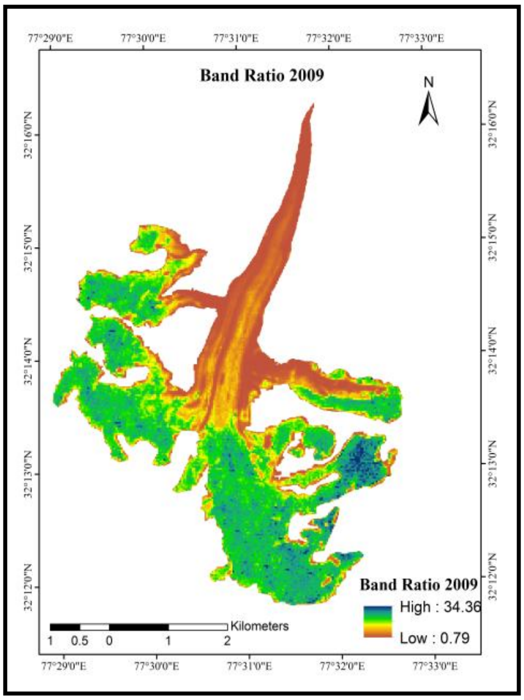
But as per result discussed in figure in 7.11(b), the average annual mass balance for time period of 1966- 2002 come as 0.30±1.67 m w.e. which is found to be very large. But in case of mass balance derived in satellite image of 16 Aug 2010, the annual mass balance as per ground value evaluated to be 0.33m w.e.

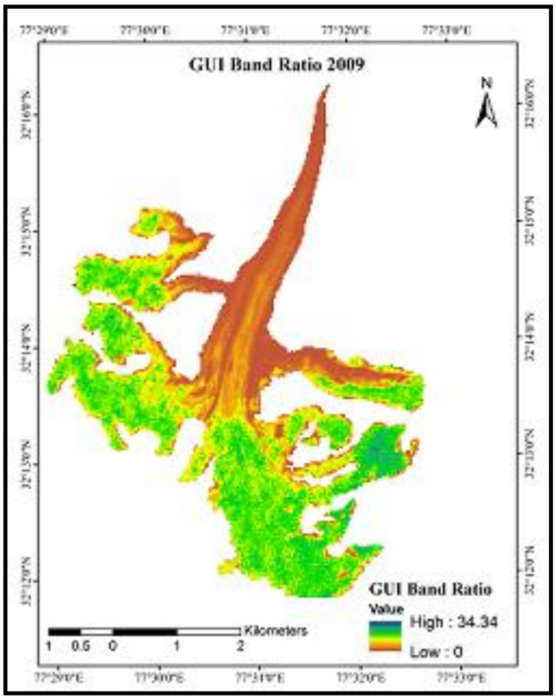
Since over estimation of method is due to the inaccuracy of DEM and low spatial resolution of data (DEM) as well as absence of timely acquisition and availability of data.

7.10 RESULTS FROM GUI

Mass balance from semi automatic technique of NDSI, Band ratio and NDSTI has been estimated from Graphical User Interface Defined in the above chapter and found that result obtained from semiautomatic techniques of NDSI and Band Ratio, without undergoing digitisation giving same result Pixel by pixel.

The results obtained while undergoing mass balance process are radiance image, reflectance image, NDSI, Band Ratio and NDSTI and Mass balance. it has been seen that all the result are matching pixel to pixel with accuracy of up to 3 decimal. The NDSI and TM value of 2009 image obtained from model and ArcGIS , Erdas Image processing techniques are as under

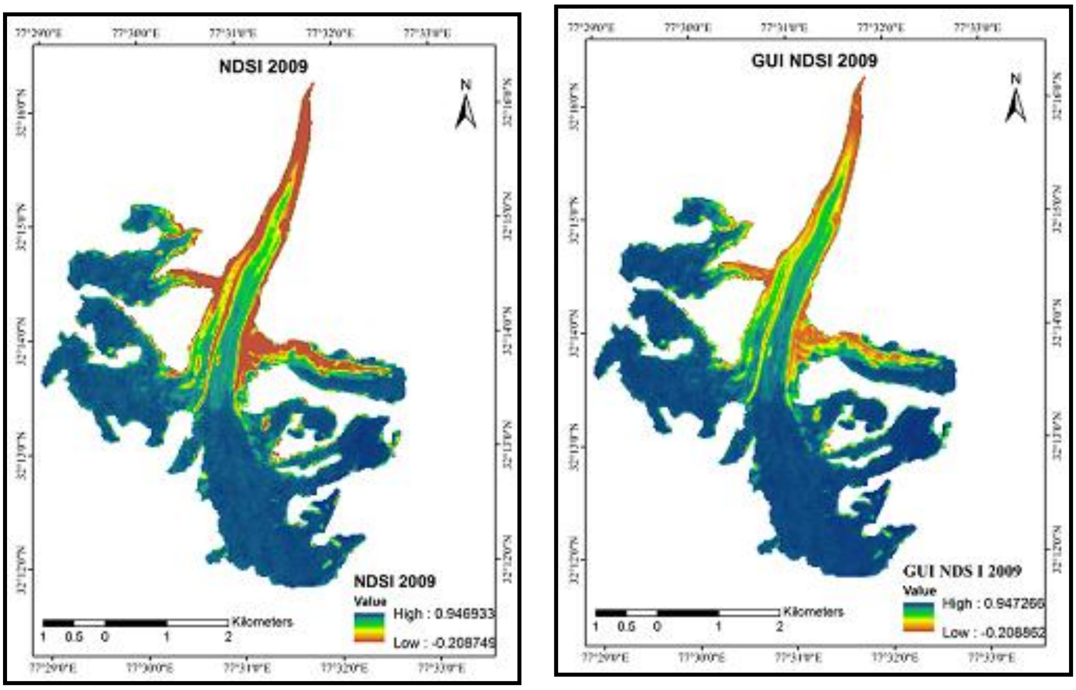




(a) ***(b)***

Figure 7.12: *Band ratio evaluated from ArcGIS (a) and Band Ratio evaluated from open source GUI developed using PyQt (b)*

Figure 7.12 shows a range of band ratio is matching between models derived Band Ratio and ArcGis based Band Ratio. Even at the pixel level values are same. Reflectance and radiance value will be checked and found to be same in range as well as in pixel values too. GUI tool will proved to be good to be use by non programmer person. Since the tool is based on specific application will going to help a lot in glacier field studies. Even individual operations like stacking, area of interest clipping, estimation of radiance and reflectance, masking and linear regression between two parameters proved to be very useful even these can be applied on any image.



(a) ***(b)***

Figure 7.13: *NDSI evaluated from ArcGIS (a) and NDSI evaluated from open source GUI developed using PyQt (b)*

The GUI derived NDSI value is exactly matching with Image processing software based derived band ratio as shown in figure 7.13. The value range is same nearly in 0.947 in GUI, whereas in normal image is 0.9469 which are found to be same. Once band ratio and NDSI is derived the next step is to apply threshold

On applying threshold NDSI image and band ratio image as 8.0 and 0.78 respectively, the result are found to be same as that calculated in raster calculator which covers accumulation and ablation areas summarized in table 7.10. On comparison of accumulation and ablation area of same images in table 7.7 and table 7.8 shows result same as that found as evaluated in GUI.

Table 7.10: *GUI derived Accumulation and ablation area and Mass balance using Satellite Image 2009*

Year	***Threshold***	***Accumulation***	***Ablation***	***AAR***	***Mass Balance***
2009	8.0(band ratio)	10.36	5.16	66.73	0.0778
2009	0.78(ndsi)	10.40	5.12	67.05	0.898

GUI Screenshots and threshold images separating zone of glaciers for NDSI and Band ratio has been shown in figure 7.14-7.17 Since accuracy of this tool is quite high and can be further used for deriving the relationship and studying the mass balance of other glacier.

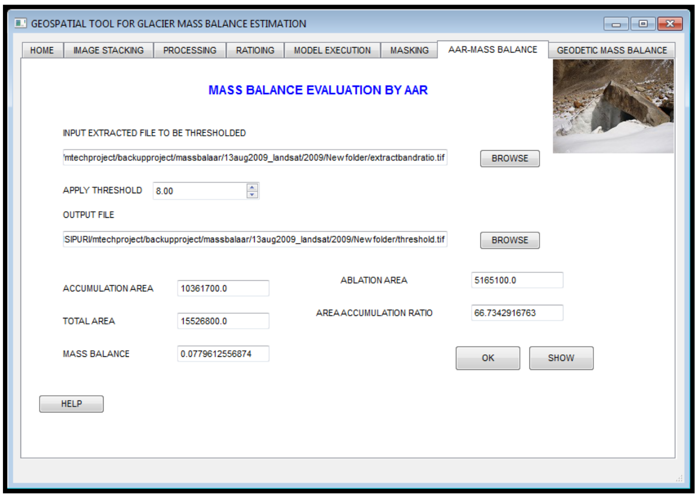


Figure 7.14: *GUI Evaluating Accumulation, Ablation Area, AAR and mass balance on a particular threshold on Band Ratio*

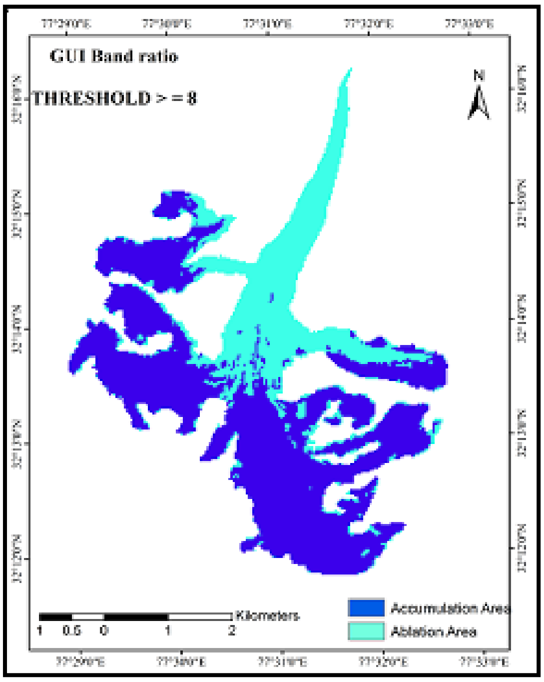


Figure 7.15*: GUI based Glacier zonation in case of applying threshold on Band Ratio*

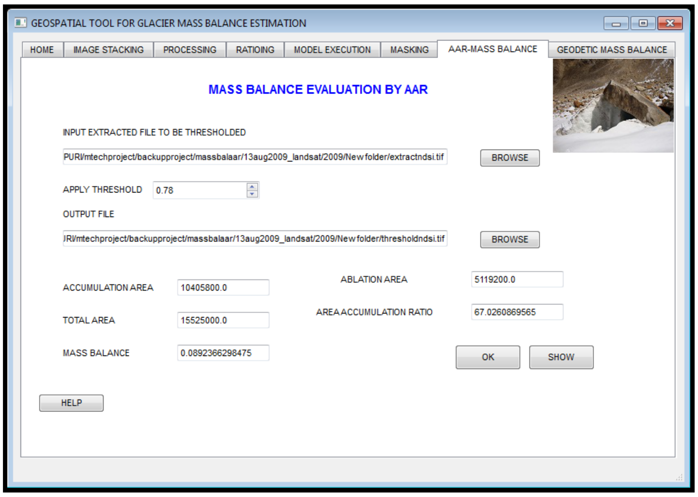


Figure7.16: *GUI Evaluating Accumulation, Ablation Area, AAR and mass balance on a particular threshold on NDSI*

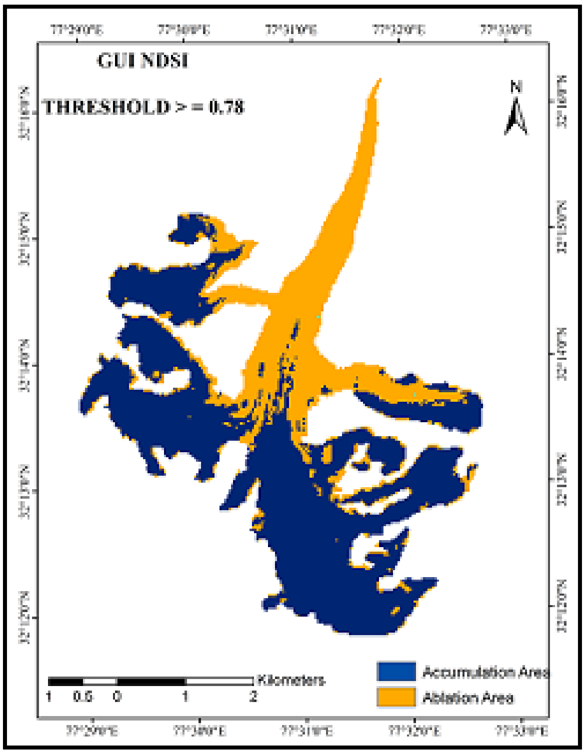


Figure 7.17: *GUI based Glacier Zonation in case of applying threshold on Band Ratio*

8. CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

- Band Ratio and NDSTI Proved to be best semi automatic glacier mapping techniques than NDSI.
- Land surface temperature also proved to be useful as based on temperature it can map zones as well as debris very well which can be misinterpreted in optical images
- The regression model evaluated is proved to be suitable and best for estimating mass balance over Chhotta Shigri Glacier with R^2 =0.95. The main advantage of this method is that mathematical model of a specific glacier can be estimated and annual mass balance can be obtained without performing any field work over and over again.
- Taking into consideration the remote areas, rugged topography, harsh climate of the glaciers, AAR method is proved to be better to do such mass balance studies with the help of remote sensing. If the field data for AAR and mass balance of a glacier for a few years are available, then mass balance for the subsequent years for same glacier can be calculated i.e. continuous monitoring of the glacier without field visit, because the glacier cannot significantly change the geometry. But if there is lack of field data, this technique may need some other parameters like elevation (ELA), the depth of the glacier, density along with the AAR to estimate glacier mass balance. AAR is considered to be one of the indicators of variations in glacier mass balance and also climatic conditions.
- Whatever deviation comes in the estimation of mass balance from the ground data may be due to acquisition time, false pixel classification , wrong visual interpretation or due to error in digitization.
- Risat-1 data is also proved to have potential for glacier mapping and monitoring as showing good correlation with the standard backscattered value.
- The Graphical user interface so formed proved to be helpful for the processing of optical data and deciding accurate threshold value for estimating mass balance. Since it provides user to estimate mass balance in less time for long term monitoring.

RECOMMENDATIONS

- The mapping of accumulation and ablation zone of glaciers can be improved, if sub pixel based classification can be done based on Hyperspectral or neural networks. Moreover taking into account the parameter of sensor saturation, slope, NDWI mask along with the Band rati0, NDSI or NDSTI can be proved to be helpful.
- AAR based mathematical Method can be generated for all glaciers which are monitored regularly so, as to reduce field trip and make full use of satellite remote sensing in all three aspects optical, thermal and microwave.
- The approach to calculate mass balance by geodetic method can be improved by using high resolution elevation data because , it is considered to reliable in terms of accuracy.
- The other techniques for estimating mass balance can be incorporated in the tool and tested on the other glacier and new feature should be incorporated and can be further

used in future glacier studies. Mass balance estimation with the use of other sensors can also be incorporated.

- Modelling approach should be used for mass balance estimation, simulation and prediction.

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APPENDIX-I

The Field photographs collected at Chhota Shigri while collecting various GCP points are depicted in the figures.

Figure 1: Photograph for Crossing River Chandra Using Basket on 21 September 2012

Figure 2: AWS installed by ISRO at Chhota Dhara for recording Meteorological Data

Figure 3: GCP Point collected through DGPS at JNU Base Camp on 21 September 2012

Figure 4: GCP Point collected through DGPS at Near Snout Position on 21 September 2012

Figure 5: GCP Point using DGPS at Lower Ablation Area at 4300metres

Figure 6: photograph taken at Lower Ablation Area on 22 September 2012

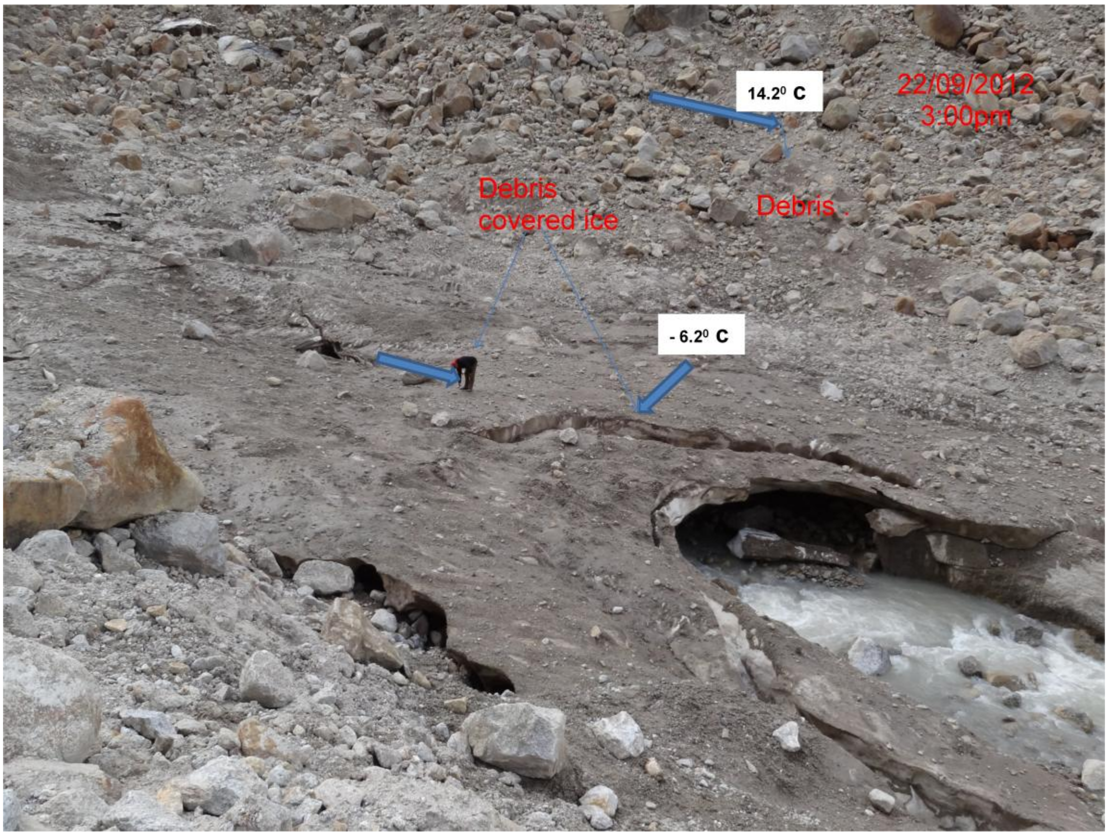

Figure 7: Surface temperature recording of glacier feature using thermal radiometer on 22 september 2012.

APPENDIX-II

It contains various output generated by the Software developed for doing image processing in Python language.

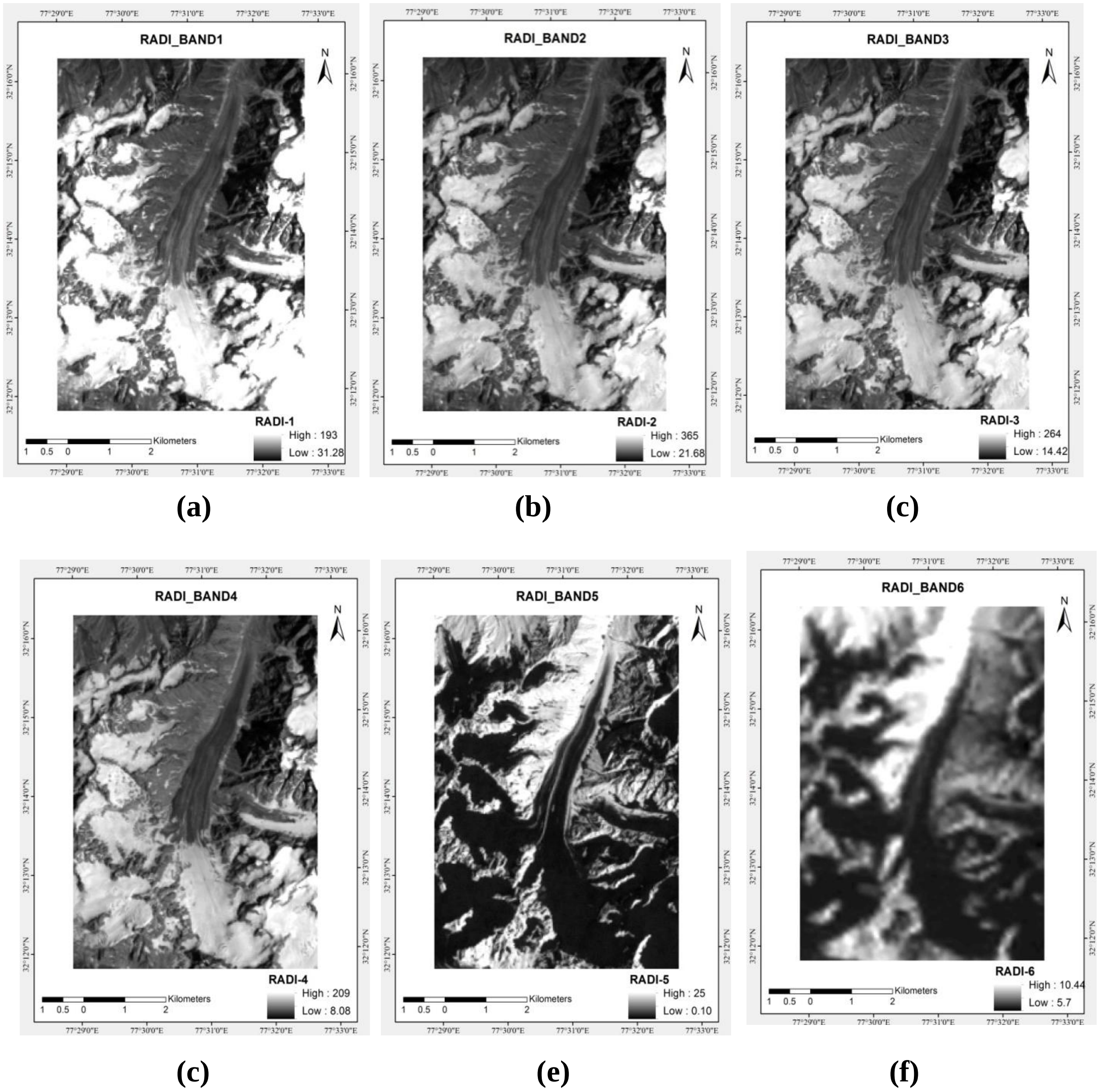

Figure 8: *Result from GUI for Radiance values for Band1, Band2, Band3, Band4, Band5, Band6 for 13 August, 2009 (a-f)*

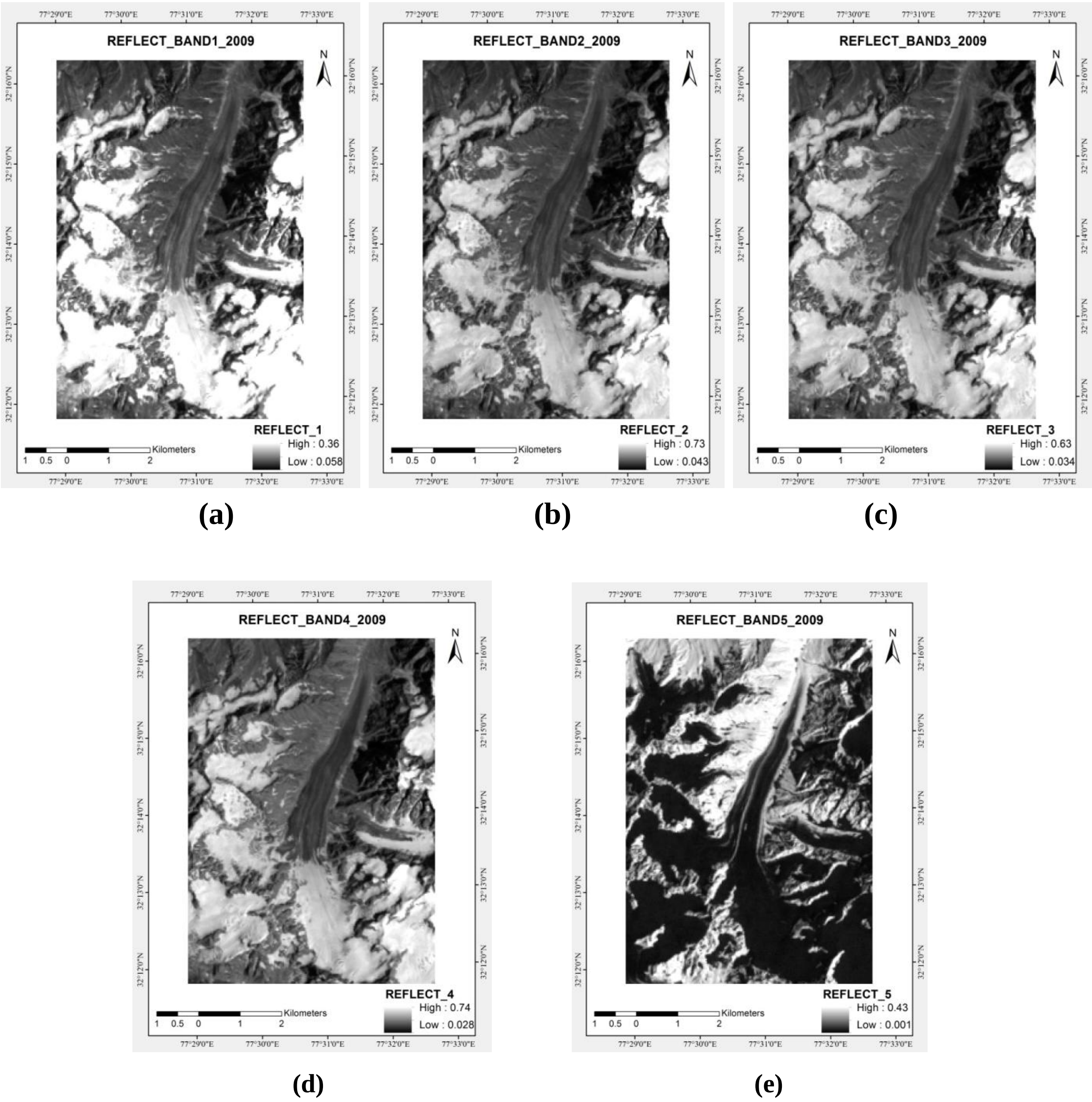

Figure 9: *Result from GUI for Reflectance values for Band1, Band2, Band3, Band4, Band5, for 13 August, 2009 (a-e)*

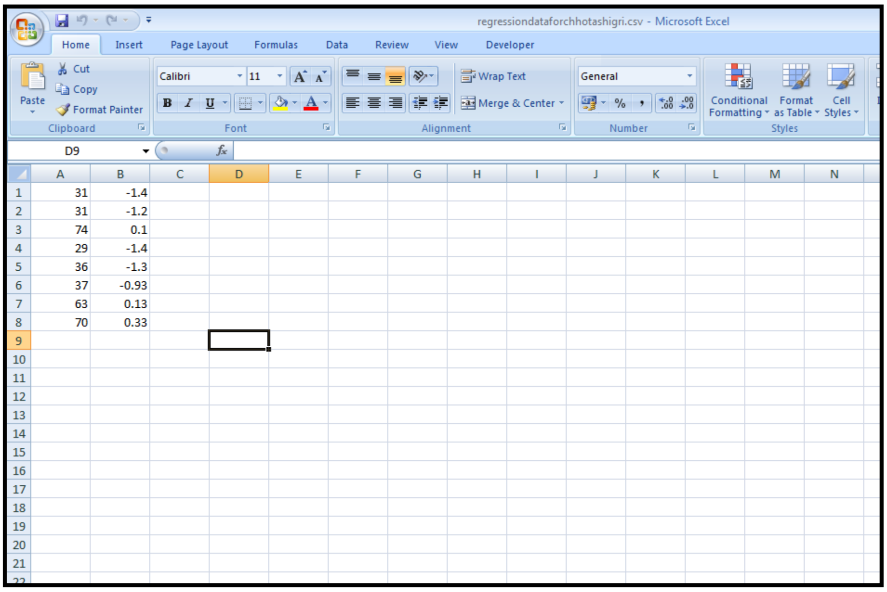

Figure10. *Parameters of AAR and Mass balance in ".csv" format*

APPENDIX-III

Sample Python code:

FOR NDSI/TM Calculation

```
import os, sys
#from __future__ import division
from osgeo import gdal
from osgeo.gdalconst import *
import matplotlib.pyplot as plt
import Image
import numpy

#read the raster data
gdal.AllRegister()
driver = gdal.GetDriverByName('HFA')
file_name1 = "C:/mansi documents/MANSI PURI/mtechproject/back up project/mass bal
aar/16_aug_2010/reflectance/reflb2.img"
dataset1 = gdal.Open(file_name1, GA_ReadOnly)
geotransform = dataset1.GetGeoTransform()
projection = dataset1.GetProjection()
band2 = dataset1.GetRasterBand(1)
print(geotransform)
print(projection)
col1=dataset1.RasterXSize
row1=dataset1.RasterYSize
print col1,row1
file_name2 = "C:/mansi documents/MANSI PURI/mtechproject/back up project/mass bal
aar/16_aug_2010/reflectance/reflb5.img"
dataset2 = gdal.Open(file_name2, GA_ReadOnly)
band5 = dataset2.GetRasterBand(1)
col2=dataset2.RasterXSize
row2=dataset2.RasterYSize
print col2,row2

# check the data type
driver = dataset2.GetDriver()
outDatase = driver.Create("C:/mansi documents/MANSI PURI/mtechproject/back up
project/mass bal aar/16_aug_2010/im.img",col1,row1,1,GDT_Float32)
outband= outDatase.GetRasterBand(1)

xBlockSize = 64
yBlockSize = 64
for i in range(0, row1, yBlockSize):
    if i + yBlockSize < row1:
        numRows = yBlockSize
    else:
```

```
        numRows = row1-i
    for j in range(0, col1, xBlockSize):
        if j + xBlockSize < col1:
            numCols = xBlockSize
        else:
            numCols = col1-j
        data5 = band5.ReadAsArray(j, i, numCols, numRows).astype(numpy.float16)
        data2 = band2.ReadAsArray(j, i, numCols, numRows).astype(numpy.float16)
        ndsi = (data2-data5)/(data2+data5)
        # do calculations here to create outData array
        outband.WriteArray(ndsi, j, i)

outband.FlushCache()
outband.GetStatistics(0, 1)
geoTransform = dataset1.GetGeoTransform()
outDatase.SetGeoTransform(geoTransform)
proj = dataset1.GetProjection()
outDatase.SetProjection(proj)
gdal.SetConfigOption('HFA_USE_RRD', 'YES')
outDatase.BuildOverviews(overviewlist=[2,4,8,16,32,64,128])
print ndsi
proj=outDatase.GetProjection()
print proj
trans = outDatase.GetGeoTransform()
print trans
data= outband.ReadAsArray()
gdal.SetConfigOption('HFA_USE_RRD', 'YES')
outDatase.BuildOverviews(overviewlist=[2,4,8,16,32,64,128])
outDatase=None
outband=None
band2=None
band5=None
print "MISSION COMPLETE"
```