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Remote Sensing of Mountain Glaciers and Related Hazards

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Abstract

Mountain glaciers are highly sensitive to temperature and precipitation fluctuations and active geomorphic agents in shaping the landforms of glaciated regions which are direct imprints of past glaciations, providing reliable evidence of the evolution of the past Cryosphere and contain important information on climatic variables. But most importantly, glaciers have aroused a lot of concern in terms of glacier area changes, thickness change, mass balance and their consequences on water resources as well as related hazards. The contribution of glacier mass loss to global sea-level rise and increasing number of glacier-related hazards are the most important and current socioeconomic concerns. Therefore, understanding the dynamics of the changes and constant monitoring of glaciers are essential for studying climate, water resource management and hydropower and also to predict and evade glacier-related hazards. The recent advances in the techniques of earth observations have proved as a boon for investigating glaciers and glacier-related hazards. Remote sensing technology enables extraction of glacier parameters such as albedo/reflection/scattering, glacier area, glacier zones and facies, equilibrium line, glacier thickness, volume, mass balance, velocity and glacier topography. The present chapter explores the prospective of remote sensing technology for understanding and surveying glaciers formed at high, inaccessible mountains and glacier-induced hazards.

Keywords: Mountain glacier, hazard, assessment, remote sensing

1. Introduction

Glaciers require standard and accurate technology to be studied. Remote sensing technologies play tremendous role for monitoring glaciers. In fact, a glacier can be considered as a large body of moving ice wherein water penetrates in the form of snow. The snow then transforms into ice by compaction and recrystallization and the ice flows through the system under its own weight and leaves the system by melting and evaporation [1]. The glacier is thus a large

body of moving ice. Therefore, glaciers store considerable amount of fresh water in frozen form. The water supply from the glaciers located in the upstream mountains is vital for sustaining and maintaining downstream cultures. The melt water from the snowpack and glaciers fulfil manifold requirements of humankind. In the dry season, the water from glaciers is released by delayed response through snow and ice melting and enhances the river runoff, therefore providing water to the downstream when there is no other source of water [2]. For instance, the melt water released from the glaciers in the Alps and Himalayas and other mountain ranges is crucially important and plays a major role in the water supply of large downstream population [3–6]. The ice sheets, ice caps and glaciers constitute 10% of the earth's land surface contributing to about 3% of the total water on earth corresponding to about 80% of the world's freshwater [7]. According to the estimate made by Meier and Bahr [8], the total area of the glaciers and ice sheets are about 680,000 km² and according to Dyurgerov and Meier [9], the same is about 785,000 km². The Hindu-Kush Himalayan region alone contains a total of 60,054 km² glaciated area, which is the largest concentration of glaciers outside the polar caps. The Hindu-Kush Himalayan region is home to about 54,252 glaciers and is aptly called as the “Water Tower of Asia” as it provides 86,000,000 m³ of water annually.

These glaciers feed the world's largest rivers such as the Ganga, Indus, Brahmaputra, Salween, Mekong, Yangtze and Huang Ho and supply water to about one billion people living downstream. The fresh water coming from the glaciers of high mountains in these rivers is an important resource for agriculture, navigation, fishing, generation of hydropower and tourism. Apart from being a boon to society, glaciers also play havoc to life and property of the people residing downstream. The mountain glaciers are a potential source of severe natural hazards [10–12]. Besides playing many roles in hydrological sectors, glaciers are also considered as a key indicator of climate. Any change in the climate is visible through glacier behavior and response. Glaciologists and climatologists carry out research on glacier changes to understand the change in the past and present climate and to predict the future changes. Contribution of glacier melt water to sea level rise under warming climate is the burning topic among the glaciologists and the hydrologists.

Glaciers form under the climatic condition when snowfall is more than snowmelt and this condition in the tropics is fulfilled at very high altitude where the temperature is very less. Therefore, the mountain glaciers are generally located at remote and inaccessible locations. Monitoring of these glaciers through ground survey is costintensive, difficult and sometimes dangerous to life. Remote sensing offers an innovative and valuable tool for gathering information about remotely located glaciers which are otherwise inaccessible and significantly capable of extending the scale of the study both spatially and temporally. In the past few decades, the remote sensing has proved to be a crucial resource for glaciologist. The advent, advancement and increase in the number and quality of earth observing sensors, the development of new technologies, algorithms, high processing capability and new methodologies have brought huge revolution in understanding the Cryospheric processes [13].

Keeping in view the importance of glaciers in society and environment, this chapter will provide information on the remote sensing data available for glaciological studies, the glacier parameters studied by remote sensing and the method of studying those parameters. The chapter will focus on the method of estimating snow and glacier area change, volumetric

change, mass change, velocity and assessment of glacier-related hazards. The chapter will broadly address two major topics: (a) study of snow and glacier parameters and (b) hazard assessments. This chapter will provide an overview of the importance, impact and the place of mountain glaciers in our social life as well in scientific research.

The objectives of the chapter are very precise and clear, that is, to endow the readers with the scope of studying various glaciological parts and subjects with remote sensing. Our aim is to make the readers familiar with mountain glaciers, their parts and dynamics and the methodology to study the same. Thus, in the chapter we will attempt to discuss about the remote sensing data types and the different glacier parameters which can be studied and derived by them. The emphasis will be given to the methodology of extracting various glaciological parameters from remotely sensed data. Figure 1 is the field photograph of Chhota Shigri glacier taken during September 2014.



Figure 1. Field photograph of a Himalayan glacier, September 2014 (Chhota Shigri, western Himalaya, India), showing debris on the glacier, the surrounding avalanche prone steep cliffs and the Bergshrend line separating the glacier body from the cliff.

2. Glacier zones and features

Glaciers form when in a year fall of snow is more than the wasting of snow and the trend continues for many years. The formation and sustenance of glacier thus are functions of climatic parameters such as precipitation and temperature. The transformation of snow into glacier ice takes place through compaction and recrystallization [14]. Snowfall, snow avalanches and snow drift are some of the accumulation processes through which glaciers gain

in mass, whereas melting, evaporation and calving are the ablation processes by which glaciers lose mass. Climate and topography play major role in determining the shape, size and type of glacier [15]. Starting from the upper elevation to the terminus, a glacier can be divided into several specific zones. A typical temperate mountain glacier consists of (1) accumulation zone, which is the upper most part of the glacier and where there is net gain of ice, and (2) ablation zone, the lower part of the glacier where there is net loss in the ice through melting, calving and evaporation. The accumulation and ablation zones are separated by equilibrium line where there is neither gain nor loss of glacier ice. The lowest part of the glacier where the glacier ends and the discharge starts is known as snout/terminus/glacier toe. A glacier is a dynamic system which along with snow and ice also transports rocks and debris avalanching on the glacier from the side valley walls. These rocks and debris materials are transported through the glacier system from upper zone to the lower zone. Below the equilibrium line, after melting of ice, these rocks and debris concentrates linearly to the sides of the glacier to form lateral moraine. When a tributary glacier meets the main glaciers, the two adjacent lateral moraines form medial moraine. Terminal and end moraines are the rocks and debris piled near the end of the glacier. When these rocks and debris appear on the surface of the glacier through melting of ice, they are called supra glacier debris. Most of the mountain glaciers are debris-covered glaciers. The debris cover on the glacier changes the interaction of glacier with the climate. Sometimes, a glacier ends with a lake near its snout. This type of lake is known as pro-glacier lake. Many times, these proglacial lakes are dammed with moraines. In the enhanced melting condition of glaciers, these lakes can breach the dam and can cause havoc [16].

3. Remote sensing of snow and glacier

The remote sensing is an art and science that can gather information about an object without being in contact with it [13]. The remote sensing system can be airborne or space-borne and uses electromagnetic radiation to collect the information about the object. When the remote sensing system uses naturally occurring radiation, it is called passive remote sensing and when the remote sensing instrument generates its own radiation, it is known as active remote sensing. A glacier surface consists of snow, firn, ice, rock, debris and water, and each component has variable properties in the different electromagnetic spectrum.

3.1. Optical visible and near infrared

The optical visible and near infrared (VNIR) regions of electromagnetic spectrum (0.4–3.0 μm) are the workhorses of remote sensing [17]. The sensors in the VNIR measure radiance radiated from the object, which is related to the reflectance and albedo of the object. Various glaciers zones such as accumulation, ablation, debris covered and water on the glacier have their own specific reflectance characteristics in the VNIR region, based on which the glacier and its various facies can be mapped (Figure 2). Snow has a very high reflectance in the visible wavelength region and a considerable low reflectance in the near-infrared and middle- and short-wave-infrared regions. The reflectivity of freshly fallen snow is very high in visible and infrared regions. Firn, which is one year old snow, has 25–30% less reflectance than snow. The

glacier ice has high reflectance in the blue (0.4–0.5 μm) and green (0.5–0.6 μm) wavelength band but sharply decreases to near zero in the red (0.6–0.7 μm) band [17]. The debris on the surface of the glacier significantly lowers the reflectance. The majority of the space-borne sensors operate in number of bands and known as multispectral. One of the most successful, longest and continuous VNIR program is the Landsat program which is continuously observing earth and gathering data since 1972 (Landsat MSS, TM, ETM+, OLI/TIR). The other optical VNIR operating sensors are ASTER, SPOT, MODIS, IRS LISS III/IV and AWiFS, Quickbird and IKONOS. Table 1 lists the spectral regions of optical bands used in Landsat TM and Table 2 presents some of the important satellite missions with their specifications.

Bands	Spectral region
Visible (VIS)	0.45–0.52 (blue)
	0.52–0.60 (green)
	0.63–0.69 (red)
Near infrared (NIR)	0.76–0.90
Short-wave infrared (SWIR)	1.55–2.35
Thermal infrared (TIR)	10.42–12.50

Table 1. The spectral region in different optical bands

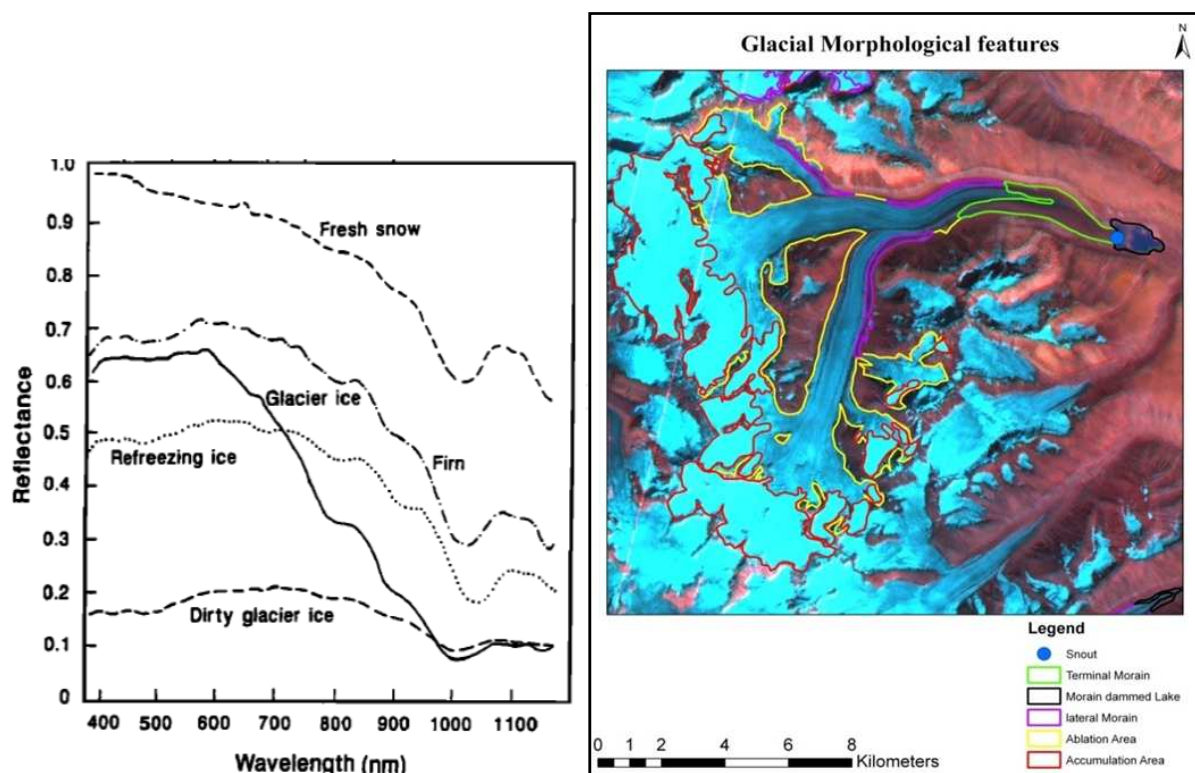


Figure 2. Spectral reflectance curves for snow and ice in different formation stages and satellite image (LISS III, September 11, 2000).

Figure 2 shows the satellite image of Samudra Tapu glacier showing different features of the glacier based on reflectance. As evident from the spectral response curve, the snow has maximum reflectance followed by firn and ice. The debris cover on the glacier has similar reflectance of surrounding rocks. The same can be confirmed from the satellite image of the Samudra Tapu glacier.

3.2. Thermal infrared

The thermal infrared (TIR) (3–15 μm) is a powerful remote sensing tool for discriminating surface objects with different temperature or emissivities [18]. Between the thermal band 8–14 μm, it is possible to measure the temperature of the earth surface and sea surface as atmosphere works as window for these wavelength regions. The surface temperature of glacier is lower than the surroundings and thus can be differentiated using thermal data. The thermally active layer of a glacier has only 10 m depth upto which the seasonal variations can be felt [17]. The most commonly used thermal band sensors for the glaciological study are AVHRR, MODIS, Landsat series and ASTER.

Platform/sensors	Launch	Number of bands	Spatial resolution	Spectral resolution
Landsat MSS	1972		80m	4MS
Landsat TM	1984		15, 30, 60/100m	PAN, 6MS, 1TIR
Landsat ETM+	1999–2003			2TIR, PAN,8MS
Landsat OLI/TIR	2013			
ASTER	1999	15, 30, 90m	14 bands	3VIS/NIR, 6SWIR, 5TIR
SPOT	1984	20m/10m	4 bands	3VIS, 1PAN
MODIS	1999	250, 500, 1000m	36 bands	VIS, TIR
Quick bird	2001	0.6m	4 bands	3VIS/NIR, PAN
IKONOS	1999	1m	4 bands	3VIS/NIR, PAN
IRS LISS III/IV, AWiFS	1988–2011	72 m to 5.8m	4 bands	VIS/NIR

Table 2. List of selected optical remote sensing satellite missions

3.3. Microwave electromagnetic spectra

Microwave spectrum is the most popular wavelength region for studying snow and glacier properties after optical VNIR. The microwave sensors can be passive (radiometer, 3–6 mm spectral range) and active (radar, 1 mm to 1 m spectral range). The atmosphere is transparent in all weather conditions for the whole microwave spectral bands, and therefore, the microwave can be used to study the glacier in all weather conditions and day and night. The major advantage of microwave in monitoring glacier is the ability of microwave signals to penetrate into snow and ice upto various depth and providing information about the internal structure of the glacier. The depth of penetration of the signals depends on the wavelengths. In the dry snow zones, the penetration has been reported to be tens of meters [19]. The L-band radar can

be significantly used for collecting information about the glaciers' internal stratigraphy. The ability to penetrate in the wet snow conditions is lesser than the dry snow. With the increase in wavelength, the ability of penetration increases. Surface roughness also influences the reflection and backscattering of microwave significantly. With the usage of synthetic aperture radar (SAR) technology, the spatial resolution of the radar remote sensing can be greatly improved. High-quality and high-resolution SAR data can be used to study glacier facies, glacier stratigraphy and other parameters such as glacier thickness and movement. Table 3 and 4 provide the details of microwave bands and satellites.

Band	Wavelength (cm)	Instrument
Ka	0.8–1.1	–
K	1.1–1.7	–
Ku	1.7–2.4	–
X	2.4–3.8	TerraSAR-X, TanDEM-X, COSMO-SkyMed
C	3.8–7.5	SIR-C, ERS 1/2, ENVISAT ASAR, RADARSAT 1/2
S	7.5–15	ALMAZ
L	15–30	JERS-1, SEASAT, ALOS PALSAR
P	30–100	–

Table 3. Microwave spectrum bands and sensors

System	Country	Year of launch	Band	Resolution (m)
SEASAT	USA	1978	L	25
ERS 1/2	Europe	1991/1995	C	30
J-ERS	Japan	1992	L	18
SIR-C	USA	1994	L	–
X-SAR	Germany/Italy	1994	C/X	15–25
Radarsat-1/2	Canada	1995/2007	C	10–100/3–100
SRTM	USA/Germany/Italy	2000	C/X	90/30
ENVISAT	Europe	2002	C	30, 150, 1000
ALOS	Japan	2006	L	7–100
TerraSAR-X	Germany	2007	X	1–16
TanDEM-X	Germany	2009	X	1–16
COSMOS-SkyMed	Italy	2009	X	1–100

Table 4. List of some selected SAR missions

3.4. Interferometric SAR

Apart from the amplitude of the returned signal, SAR also exploits the phase of the returning signals to extract information of the target. The interferometric SAR (InSAR) technique is based on the phase difference of at least two complex SAR images acquired from either different orbit positions (single pass) or different times (repeat pass). SAR interferometry uses the phase difference between the two returned signals to measure the slight changes in the earth surface. With the single pass interferometry, where the radar is equipped with two antennas, the same point on the ground can be measured at the same time with slightly different angles and this can produce stereo images. These images can be used to produce highly accurate topographic information of the point and can be used to prepare height maps. The InSAR is highly suitable for computing change in the surface thickness of glaciers over large spatial and temporal scales. SRTM is the best example of single pass interferometry, which has been used to produce high-precision global DEM. Tandem data of ERS 1 and 2 (1996/1997) were the first repeat pass SAR data with interferometric generation capability. TerraSAR-X add-on for Digital Elevation Measurement (TanDEM-X) is the new member of InSAR family along with SRTM, consisting of two satellites TerraSAR-X and TanDEM-X developed by German Aerospace Centre (DLR) and Astrium GmbH. The TanDEM-X (TDX) was launched in June 2010 as an extension of TerraSAR-X in a close formation which enables stereoscopic views. The main aim of this mission was to collect interferometric data over entire global to provide a homogeneous high-resolution global DEM with a relative vertical accuracy of better than 2m within a horizontal resolution of 12 m [20]. The advantage of this single pass bistatic mission is generation of high-quality accurate DEM against low coherence and limited accuracy of data from repeat pass mission. The generation of DEM from InSAR procedure involves interferometry generation, phase unwrapping, multilooking, reflattening, phase to height conversion and geocoding [21]. From the phase difference of returned signals from the two antennas, an interferogram is generated. The phase in an interferogram is influenced by the geometric effects and the topography of the target assuming no movement of the target [22]. By removing the geometric effects, the elevation of a target can be obtained and a DEM can be created [22]. The DEM created by InSAR method is highly accurate and can be used to derive the elevation change of the glacier along with other topographical parameters. The elevation change can further be used to calculate the mass balance of the glaciers. The phase from repeat pass interferometry is the key source for studying small coherent motions of the target between the imaging times. In repeat pass interferometry, the phase difference from the target acquired by the antenna for a nominal time interval enables the measurement of motion of the target during the small acquisition interval. The velocity of the target is obtained by removing the phase obtained due to topography and retaining only the motion phase. The ERS1/2 tandem mission has been extensively used to derive motion of various objects [23]. Figure 3 demonstrates the acquisition geometry of radar interferometry. SAR1 and SAR2 fly on parallel tracks and view the terrain simultaneously from slightly different directions (single pass interferometry) [24]. The technique of InSAR is based on the phase of returned signals from SAR1 and SAR2. The phase difference resulting from the fractional difference of wavelengths of pulse travel time would provide a parallax due to the topography and the shift in location of the target due to motion [13]. The InSAR technique can be exploited to obtain the topographical information and the motion of the target at high precision.

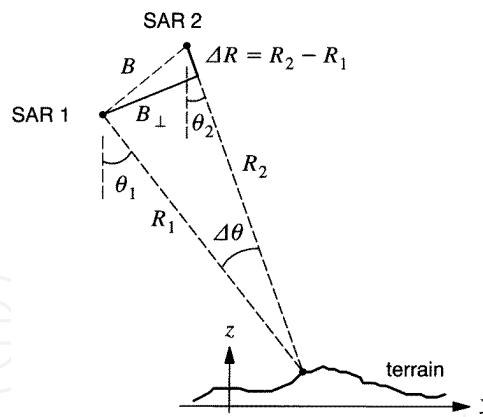


Figure 3. Principal of InSAR acquisition geometry (figure from Balmer and Hartle [24]).

4. Glacier parameters studied with remote sensing

4.1. Snow cover mapping and snowpack properties retrieval

Snow is the most essential and fundamental constituent of a glacier and a key component of earth's energy balance [25]. The mountain snow and the subsequent snow melt can play a dominant role in modulating the local to regional climate and hydrology [26]. The knowledge of snow coverage and snow properties such as albedo, snow grain size, snow depth, snow density and snow water equivalent (SWE) are crucial to know and predict the snow melt. The unique characteristics of snow like high reflectance relative to other surrounding materials (rocks, water, clouds) in the visible part and low reflectance in the mid-infrared part of the spectrum are the foundation of snow cover mapping from space in optical remote sensing [25]. Dozier and others [26] have developed an automatic algorithm to distinguish snow from soil, rocks and clouds by using ratio of reflectance in the VNIR wavelengths (Landsat TM band 2 and 5) which is known as normalized differential snow index (NDSI). According to Dozier [27], a normalized difference snow index (NDSI) is calculated from reflectance in bands at wavelengths where snow is bright (e.g., TM band 2 or MODIS band 1) and where it is dark (e.g., TM band 5 or MODIS band 6), along with a band used for threshold brightness (e.g., TM band 4 or MODIS band 2):

$$\text{NDSI} = \frac{\text{TM bands 2} - \text{TM bands 5}}{\text{TM bands 2} + \text{TM bands 5}} \quad (1)$$

A snow cover area is mapped when $\text{NDSI} > 0.4$ (Figure 4). Although the snow cover can be mapped with a number of remote sensing devices, multispectral bands in the optical VNIR region of electromagnetic spectrum are most suitable and widely used. In general, the VNIR bands of Landsat MSS, Landsat TM, AVHRR, MODIS, SPOT, ASTER, and IRS have been extensively utilized to map the world's snow cover area. Apart from snow cover mapping,

optical VNIR remote sensing has little use in retrieving snow pack properties such as snow depth and SWE. SWE is the most essential snowpack properties in the sense that it represents the total amount of water available if the snowpack has to melt instantaneously [28]. However, in comparison with snow mapping, retrieval of SWE and snow depth through remote sensing has limited success till date; only microwave remote sensing offers measurement of snow depth and SWE as there is penetration through the snowpack at these wavelengths [22]. Most of the studies have used empirical relations to retrieve SWE. The passive microwave radiometers have been used to retrieve SWE since 1978 [29]. Chang and others [29] have used the difference in brightness temperature at 19 and 37 GHz in the SWE retrieval algorithm to derive SWE from passive microwave. They have used radiative transfer calculation to derive snow depth from SMMR data. The Advanced Microwave Scanning Radiometer–Earth Observing System (AMSR-E) has been used to provide global SWE product since 2002 [30, 31]. The most recent methods of SWE and snow depth retrieval use active microwave data. Rott and others [32] have used Ku-band and X-band for SWE retrieval.



Figure 4. NDSI of Gangotri glacier derived from IRS LISS III image, September 11, 2000, for ablation season. The white part is the snow covered area and the grey is the non snow areas.

4.2. Glacier surface temperature

In global warming situation, the glacier surface temperature is the most important parameter to study the effect of climate change. However, use of traditional method of measuring surface

temperature is difficult in mountain terrains. Thermal bands from satellite data provide an excellent alternative for estimating temperatures. TIR can be used to deduce the temperature of snow, ice, clean glacier and debris-covered glaciers. The most widely used TIR sensors are Landsat ETM+, Landsat OLI/TIR, ASTER and MODIS to extract the surface temperature of glaciated areas. In the longer wavelength region, snow acts as a perfect black body. In the infrared region, the strong absorption by snow allows the estimation of temperature from thermal bands [33]. To estimate the surface temperature, the digital number (DN) is converted into radiance. The radiance is converted into surface radiance by reference channel emissivity (RCE) method [33], which then can be converted into surface temperature. The conversion of top-of-the atmosphere (TOA) radiance to surface radiance can be done by following Ref. [34]. Barsi and others [35] have provided a formula to calculate the surface temperature:

$$T_{\text{surface}} = \frac{K2}{\ln[K1 + 1 / LT]} \quad (2)$$

where T_{surface} is temperature in Kelvin, K1 and K2 are the calibration constants and L_T is surface radiance calculated as:

$$L_T = L_{\text{TOA}} - L_v - \tau(1 - \varepsilon) \times L_D / (\tau \times \varepsilon) \quad (3)$$

where L_{TOA} is TOA radiance, L_v is upwelling spectral radiance between surface and sensor, L_D is downwelling spectral radiance from sky, τ is atmospheric transmittance and ε is the surface emissivity. With the use of thermal band data, it is possible to map the debris-covered glaciers and also mapping of supra and pro glacial lakes can be done with the thermal data. Figure 5 illustrates the thermal map of glaciated region of Chandra-Bhaga basin, Indian Himalaya, using thermal band of Landsat ETM+ for the year 2000.

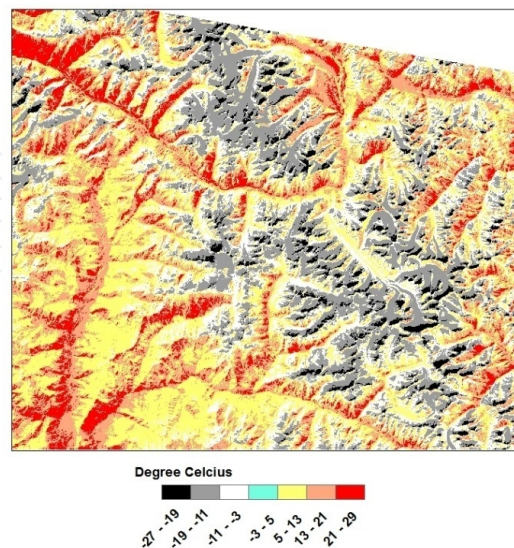


Figure 5. Temperature image of Chandra-Bhaga basin Himachal Himalaya, India, derived from the thermal band of Landsat ETM+ data during ablation season.

4.3. Glacier inventory, monitoring and mapping

Satellite is the backbone of World Glacier Inventory (WGI) and monitoring. Development of new tools and techniques in remote sensing and availability of advanced high-resolution satellite data have brought a revolution in the inventory of world's mountain glaciers. The history of global glacier inventory goes back to 1957–1958, the International Geophysical years, when the inventory of global glaciers was first proposed in the form of national lists of glaciers [35]. This list later known to be WGI under the leadership of Muller and the status was assessed by World Glacier Monitoring Service (WGMS1989), and the digital version of the data was made available by National Snow and Ice Data Center (NSIDC), Boulder, Colorado, USA [35]. A large-scale inventory of global glaciers has been initiated with Global Ice Measurements from Space (GLIMS) in 1995. The GLIMS project was designed to monitor the world's glaciers primarily using data from optical satellite instruments, such as ASTER. GLIMS provide coverage of 58% of global glacierized area with extensive set of attributes [35]. The most recent global inventory is the Randolph Glacier Inventory (RGI), which provides complete collection of digital outlines of global glacierized area excluding ice sheets. The RGI was developed to meet the needs of the fifth assessment of the IPCC on climate change for estimates of past and future mass balance [35]. Satellite images from Landsat 5 TM, Landsat 7 ETM+, ASTER and SPOT 5 HRS have been used to derive the outline of glaciers for RGI.

There are numerous methods to map and delineate mountain glaciers. One of the best methods is the manual delineation of the glaciers through visual interpretation of satellite images acquired during end of ablation season with no recent snowfall. On a false color composite (FCC) image with enhanced contrast, the visual inspection and hence delineation of glacier and other facies become easier. However, to map and monitor glaciers on regional scale, the manual delineation is very cumbersome and time taking and hence not very useful. From the various methods of glacier delineation and mapping on regional scale, the band rationing is simple, robust, accurate, time effective and most suitable [36–39]. The band ratio method is based on the simple rationing of two bands, that is, TM3 and TM5 (RED/SWIR) or TM4 and TM5 (NIR/SWIR) or combination of two bands (NDSI) with application of a threshold [39] with an additional threshold of TM1. The band ratios strongly enhance a specific surface type as well as reduce the bias in illumination from the terrain at the same time. The band ratios method is based on the contrasting response of glacier in the visible and SWIR regions. When the high reflectance of glacier in the VNIR region is divided by the low reflectance in the SWIR region, a high ratio value results [40]. By applying a threshold value, the glacier can be separated from the surrounding rock, soil and vegetation by setting the value above the threshold to black and all others to white (Figure 6). The ratio of TM3/TM5 (RED/SWIR) has the advantage over TM4/TM5 in the sense that it works better in shadows and with thin debris-covered glacier [33, 36, 38]. However, when TM4/TM5 is used, the threshold of TM1 is not required for the fact that TM4 is not much sensitive to atmospheric scattering as TM3 and also rocks in shadows are not mapped [39]. However, Paul and Hendriks [40] have found the NDSI method to be better than the TM3/TM5 method. Andreassen and others [41] have demonstrated the robustness and simplicity of the band ratio method for mapping of glaciers.



Figure 6. Glacier delineation with NDSI showing glaciated (white) and non-glaciated (black) regions, Chandra-Bhaga basin, Himachal Himalaya, India, obtained from IRS LISS III dated September 11, 2000, data.

4.4. Glacier facies mapping with SAR

SAR data can be efficiently used to distinguish the different zones of glacier such as dry snow zone, percolation zone, wet snow zone, firn zone, ablation zone and debris cover. However, the interpretation of SAR data is complicated and difficult than the optical data. The wavelength, polarization, incidence angle, dielectric properties, roughness and grain size are the important glacier parameters that crucially affect the strength of SAR backscatter signals. Based on the contrasting backscatter, the different glacier zones can be mapped with SAR data. Rau and others [42] have identified various radar glacier zones by their backscattering characteristics. These zone are dry snow radar zone, frozen percolation radar zone, wet snow radar zone and bare ice radar zone. Partington [43] has proposed a methodology for facies mapping using multitemporal SAR data. This method involves generation of composite images using winter, early summer and late summer radar backscatter images. Composites are generated by assigning blue to the winter image, green to the late summer image and red to the early summer image. This color combination SAR image is useful to identify different

glacier zones due to tonal variations (Figure 7). The color composite will be overlaid on a digital elevation model (DEM). This combination helps to obtain the elevation value as well as backscatter coefficient value for any particular pixel to carry out quantitative analysis. Generally, the winter image defines maximum freezing conditions and late summer image defines maximum melt conditions. This methodology is based on the principle that different zones have typical backscatter signatures related to the snow pack characteristics, influenced by the balance of accumulation and melt at different altitudes.

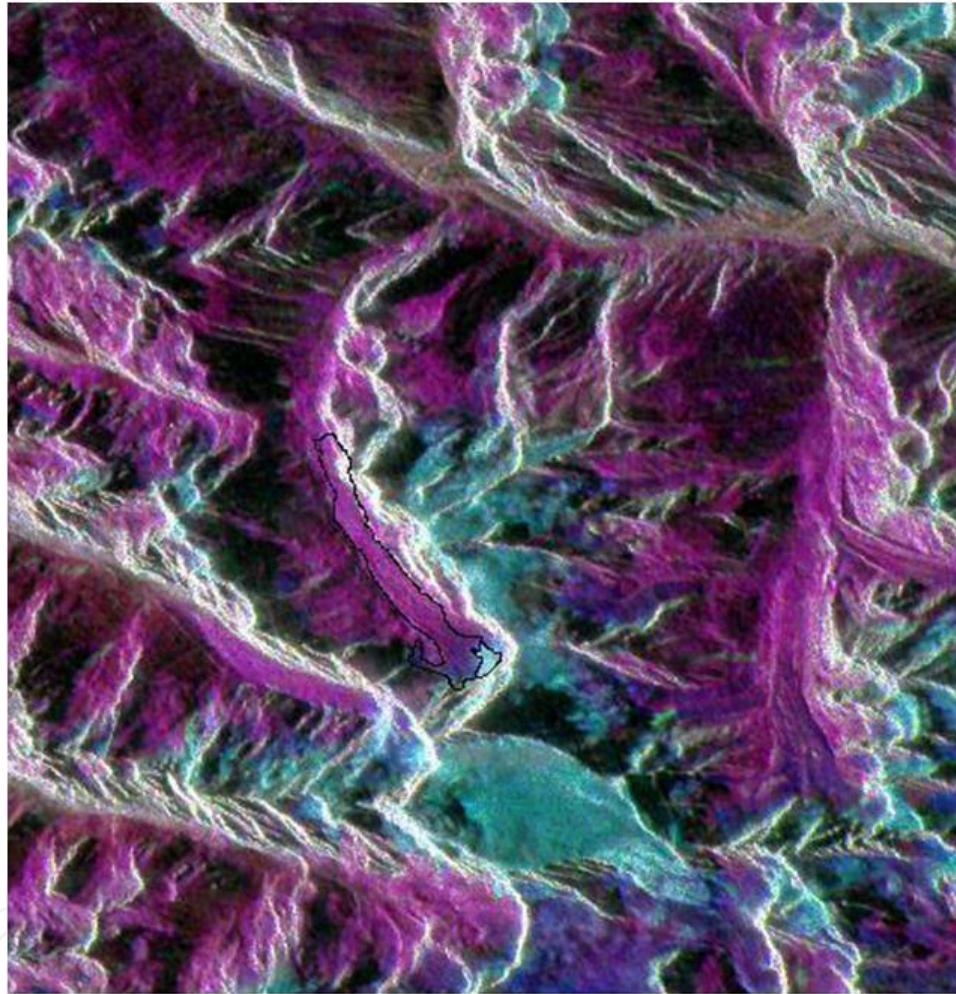


Figure 7. FCC from multitemporal ENVISAT SAR data showing Hamtah glacier region. Three images from winter, early summer and summer have been taken to make the FCC image. In the image, the cyan color indicates fresh snow, blue indicates firn and violet indicates debris cover.

4.5. Equilibrium line altitude extraction

The equilibrium line elevation can be extracted by overlaying an optical image on a DEM. The snowline altitude at the end of ablation season is supposed to be coinciding with the equilibrium line altitude. The cloud-free VNIR optical images with no recent snowfall of ablation season are selected for this purpose. To demarcate ELA on glacier and to differentiate snow

from firn and ice, reflectance images are classified (supervised classification by giving maximum number of training classes for better accuracy). The classified images are then draped over a DEM (SRTM has been proved to be good for the purpose) to get elevation points. Before extracting the elevation points, the DEM and the optical images are brought to a common platform in terms of resolution and datum, and hence they are required to be reprojected, resampled and co-registered properly with each other. The classified images are draped on the DEM, and elevation points are determined along the demarcated line for the glacier. The average of the elevations along the line is considered as the ELA of the glacier (Figure 8).

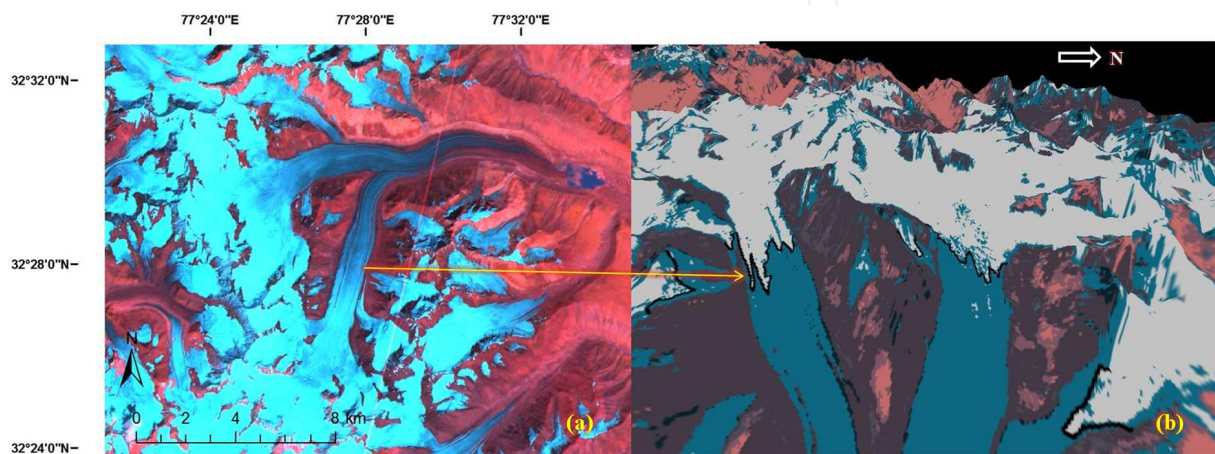


Figure 8. Method of ELA extraction on image: (a) reflectance image from IRS LISS III for Samudra Tapu glacier; (b) the demarcated ELA on the classified LISS III image dated September 11, 2000, draped on SRTM DEM.

4.6. Glacier topography and morphometry

If climate is the driving force behind the glacier change, the glacier topographical parameters are the controlling factors that modulate the changes. Glacial topography is an important factor that explains the variability in the recessional rates of glaciers of the same basin [44]. The topographical parameters of a glacier can be listed as maximum, minimum, median and mean elevation of the glacier, the altitude range of the glacier, slope and orientation of the glacier. Derivation of topographical parameters of the glacier requires DEMs. Properly co-registered visible optical image overlaid on a DEM can be used to extract the maximum elevation of the glacier, the elevation of snout and equilibrium line altitude. SRTM and ASTER GDEM are the two freely available global DEM which have been extensively used to derive the topographical parameters of the glaciers along with the used of images from Landsat series, ASTER, SPOT and IRS series. The average slope and mean orientation of the glacier can be extracted from the SRTM or ASTER GDEM in ArcGIS (Figure 9). The compactness ratio, the relative upslope area and the slope of the upslope area are the glacier indices which provide the information about the contribution of the avalanching from the surrounding to the glacier and affect the mass balance of the glacier. The method of calculation of these glacier indices has been discussed in Refs [45, 46]. The compactness ratio is the measure of glacier morphometry and

can be derived from the formula $(4\pi \text{area})/(\text{perimeter})^2$ following Refs [45, 46]. The relative upslope area is defined as the ratio of the upslope area to glacier surface area and represents the contribution of the surrounding upslope area in the glacier mass balance. The upslope area and the mean slope of the upslope area of glaciers are calculated from the optical data in the visible region along with a DEM in the ArcGIS environment.

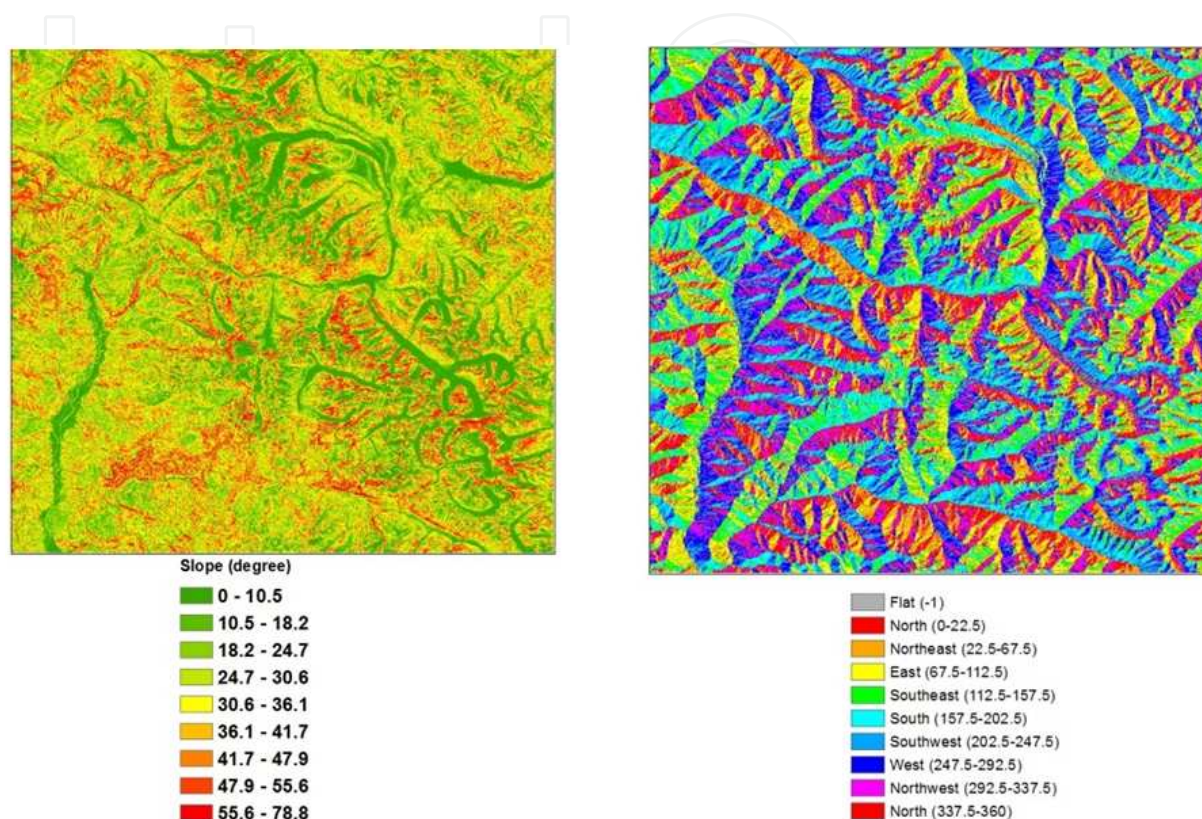


Figure 9. Slope and aspect map derived from SRTM DEM for Chandra-Bhaga basin, Indian Himalaya.

4.7. Glacier thickness and mass balance

Glacier mass balance is the most important glacier parameter to be measured and is of interest to glaciologist, climatologist and hydrologists. In a hydrological year, the net gain or loss of the glacier mass is known as glacier mass balance. The glacier mass balance is direct, undelayed and un-filtered response of climate. Mass balance of glaciers reflects the precipitation and temperature conditions surrounding the glacier and hence is studied to infer the condition and/or variability of climate. Due to the remote location, vastness and irrepressible nature of the Himalayan glaciers, remote sensing-based techniques offer effective alternatives to field-based measurement of mass balance of glaciers. The direct/glaciological surveys of glaciers for mass balance is not feasible for a large number of glaciers as many glaciers does not fulfill the criteria of benchmark glaciers in terms of size, length, geometry, altitudinal range, accessibility and safety. Geodetic mass balance measurement derived from elevation comparisons method complements glaciological method for large number of glaciers. In this method, the change in surface elevation of glaciers is derived by differencing two DEMs of different times. The brief

methodology of deriving glacier mass change from DEMs has been illustrated by methodological chart in Figure 10.

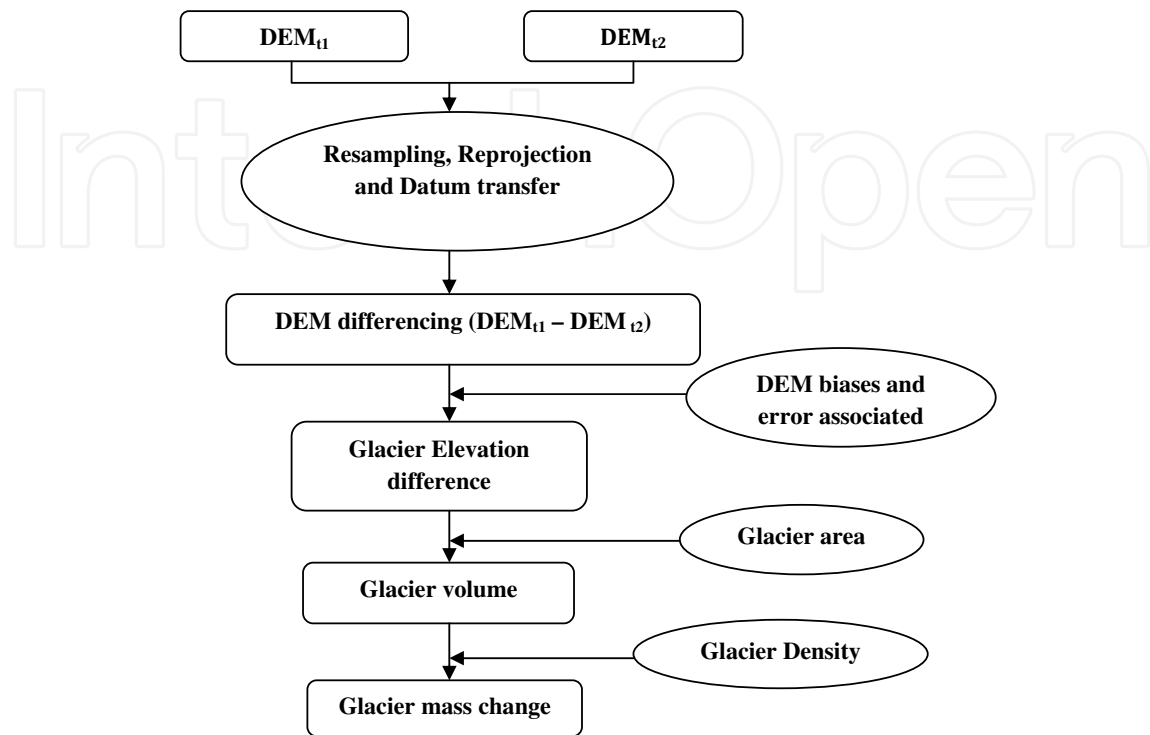


Figure 10. Flow chart showing the methodology of estimating geodetic mass balance of glaciers.

The change in elevation is converted into volume change by multiplying the surface thickness change with the area of the glacier. Now using the density of glacier, the change in volume is converted into mass change.

$$dv_z = A \sum dh_z \quad (4)$$

$$\frac{dv}{dt} = A \sum_1^z \frac{dh}{dt} \quad (5)$$

$$\frac{dm}{dt} = \rho \sum_1^z \frac{dv}{dt} \quad (6)$$

where dv_z is volume, dh_z is the elevation change curve, dm is the mass change, A is area and ρ is glacier density. The estimation of mass balance through elevation comparisons method has become frequent with the increasing number of available elevation measurements from satellites data such as ICESat, TanDEM-X, SPOT5 and SRTM and aircrafts [47, 48]. The geodetic

mass balance has been found to be more accurate for longer periods [49] and has also been used to correct the biases in the in-situ direct measurement [50, 51]. Besides, due to the ability of large spatial coverage of satellite data, the method is able to determine mass balance on regional scale [39, 48]. However, the most vital assumption in converting mass change from elevation change is the density of snow/ice lost or gained [52, 53]. In geodetic method, glacier surface elevation is converted into volume change and with the knowledge of density of material lost or gained; the volume is converted into mass change [54]. It is assumed that the density profile remains unchanged and only ice is lost or gained from glacier surface [14, 51]. The assumption of glacier density is taken from Sorge's law, which states that "the density of snow at a given depth below the surface does not change with time" given rates of melting near the surface and refreezing at depth are constant and equal. It follows from Sorge's law that a change of glacier thickness can be converted to an equivalent change of mass by multiplying by the density of glacier ice [47]. Figure 11 shows the elevation change map of a glacier in Chandra basin derived by subtracting SRTM of the year 2000 from TanDEM-X DEM of the year 2011.

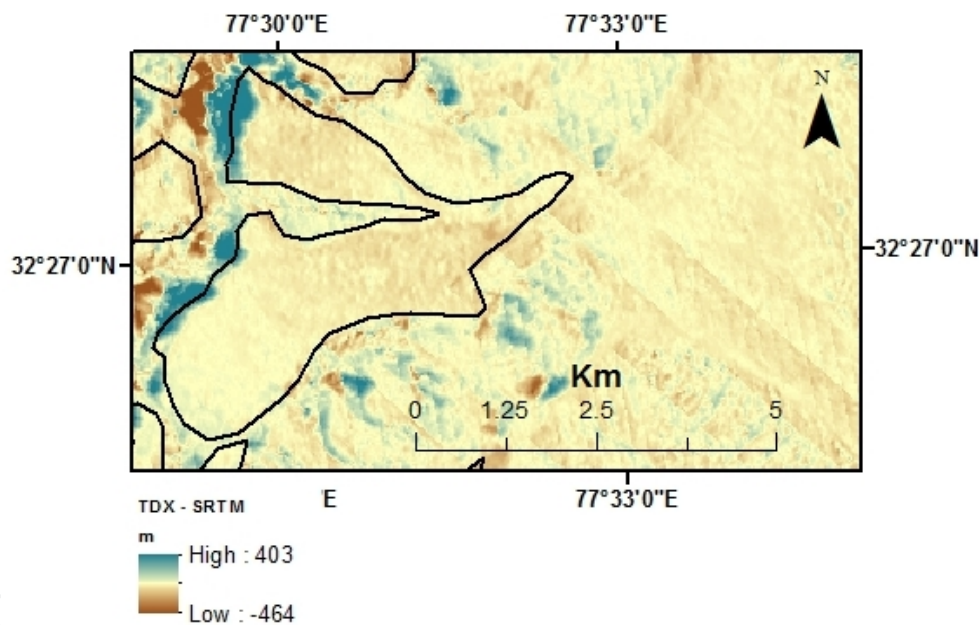


Figure 11. Elevation change map of a glacier of Chandra basin, Himachal Himalaya, India, derived by subtracting SRTM (2000) from TanDEM-X DEM (2011).

4.8. AAR method of mass balance estimation

The mass balance of mountain glaciers at regional scale can be inferred from accumulation–area ratio (AAR) and ELA derived from satellite data. The method is discussed elaborately by Kulkarni [55], who has used this to derive the mass balance of Himalayan glaciers using AAR method on basin scale. The method is based on the relation between AAR/ELA and mass balance of glacier. The AAR is the ratio between the accumulation area and the area of an entire glacier [56]. The AAR of a glacier is characteristic of glacier mass balance and also indicates

the state of health of glacier. AAR of a glacier is closely linked with its mass balance. The variation in the AAR of a glacier from year to year can be used as an indicator of variation in net mass balance [14]. Since it is practically not feasible to monitor large number of glaciers on field, hence even the mass balance data of benchmark glaciers are not available for long time series. AAR method has been used as an alternative to estimate the mass balance of glaciers at many regions [55]. This method involves establishing a relationship between AAR and specific mass balance from long-term field observation. A regression equation is constructed between AAR and mass balance with AAR on the x -axis and specific mass balance on the y -axis. The equation obtained is then used to derive mass balance by using AAR values estimated from remote sensing. The mass balance of glaciers can be estimated through this method by using remote sensing data for the periods during which field data are not available. AAR can easily be determined from satellite images. Landsat data, IRS data, ASTER data at medium-resolution scale and SPOT, Quickbird and IKONOS data at higher scale can be utilized to obtain AAR at high precision. To determine the AAR, images at the end of ablation season without cloud cover and recent snowfall are required. The accumulation area can be easily determined by differentiating accumulation zone from ablation zone either manually or by various classification methods. The division of accumulation area from the total glacier area will give the AAR. In Figure 12, an equation has been developed from the linear relation between the specific mass balance and the AAR of Chhota Shigri glacier from the field. From the relation, the following linear equation has been obtained:

$$y = 0.038x - 2.455 \quad (7)$$

In this equation, the x is AAR of the glacier and y is specific mass balance. If we derive AAR from remote sensing data, from the above equation we can compute the specific mass balance of the glacier.

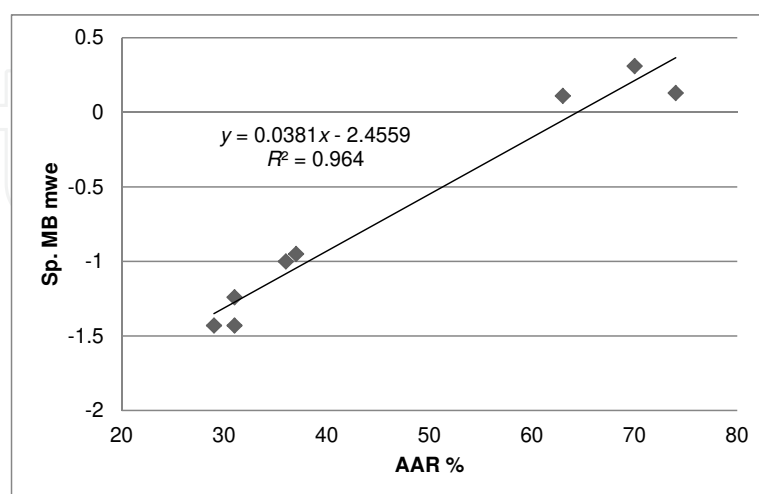


Figure 12. Example of relationship between specific mass balance and AAR, established from field data of Chhota Shigri glacier (data from Ramanathan 2011).

4.9. Glacier velocity

4.9.1. Glacier velocity with feature tracking

Study of glacier velocity provides an understanding of various ongoing dynamical processes of the glacier such as ice flow and ice instabilities, ice flux, mass transportation, development of surge and also the formation and growth of glacier lakes and associated hazards [37, 39]. As the global temperature is reported and predicted to be rising, the glaciers on average are experiencing negative mass balance. In response to the negative mass balance, glacier surface velocity is found to be slowing down in mountainous regions [57, 58]. The glacier surface velocity and movement can be tracked by both optical and SAR satellite data on regional scale. With sequential satellite imageries, the glacier velocity can be determined by tracking glacier surface features such as crevasses and big boulders. This method of calculating glacier velocity with repeat optical and SAR satellite data is known as feature tracking method in general, image matching in optical domain and offset tracking in microwave domain [39]. The temporal baseline in the optical domain can range from weeks to years whereas in the microwave domain it is within weeks. The key point of image matching is the precise co-registration and cross-correlation of the two repeat pass images. Also, the temporal baseline of the repeat images should be such that the displacement of the glacier should not be larger than the accuracy of the method and surface changes due to melting, snowfall and deformation should be very small so that the intensity can be matched properly [39].

A correlation matching is commonly used to obtain both azimuth and range-direction offsets based on intensity pattern patches of two repeat-pass SAR image acquisitions. Through oversampling of the correlation surface, the matching peak can be determined to a small fraction of a pixel. The range offset and the azimuth offset are detected from cross-correlation matching. The successful estimation of the local image offsets depends on the presence of nearly identical features in the two SAR images at the scale of the employed patches. If coherence is retained, the speckle pattern of the two images is correlated and tracking with small image patches can be performed to remarkable accuracy.

The most popular and widely used optical repeat pass satellite images to determine glacier velocity are from Landsat TM, Landsat ETM+ pan, ASTER and SPOT [59, 60]. In the microwave realm, the Envisat ASAR, ALOS PALSAR and TerraSAR-X have been used for offset tracking to calculate glacier surface flow.

In the feature matching technique, the repeat images are co-registered by cross-correlation applied on stable nonmoving areas. Glacier features such as crevasses or debris and big rock boulders which are detectable in images are generally preferred for tracking [61]. The glacier velocity can be determined from the temporal separation and the surface displacement. In recent years with the advent sophisticated computer software and tools as well as high precision remote sensing data, many glaciologists have determined the glacier flow velocity successfully with high accuracy. Luckman and others, Quiney and others and Rankl and others [61–63] have shown that the technique of feature/offset tracking is suitable for Himalayan glaciers due to the presence of respective features.

In the example shown in Figure 13, SAR intensity tracking technique is used for glacier 2-D velocity estimation. The TerraSAR-X high-resolution spotlight mode images acquired on September 27 and October 8, 2012, are used. These images are acquired over the Gangotri glacier, Uttarakhand, India. The estimated surface velocity is varying from 0.1 to 1.1 cm/day over glaciated area (along the medial axis from the accumulation zone to the snout).

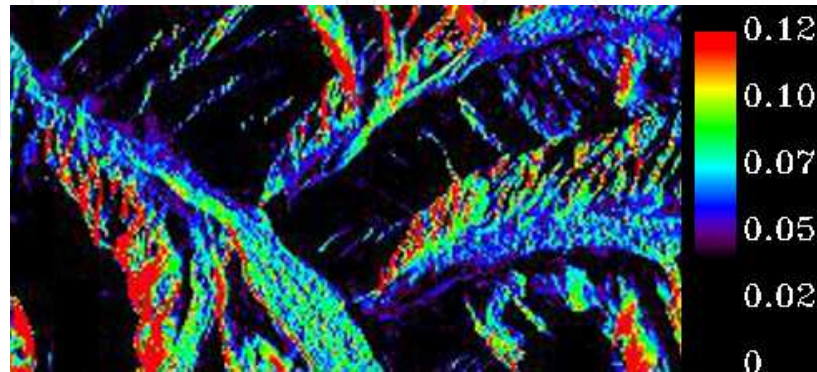


Figure 13. Gangotri glacier velocity estimated using offset tracking method employing TerraSAR-X images. The velocity values are in cm/day (figure and results provided by M. Surendar, CSRE, IIT Powai).

4.9.2. Glacier velocity using SAR interferometry

Goldstein and others [64] for the first time have determined the glacier surface velocity from InSAR data. In InSAR technique, the phase information of radar acquisition from two receiving antennas, separated in either time (repeat track) or space (single track), is used. Two SAR images will have a different distance from target when they are taken from an orbit separated by temporally/spatially from each other. An interferogram can be generated by subtracting the phase of the two images, the phases of which contain range difference. When there is no motion of the target, the phase is influenced by topographical and geometrical effects. If the geometrical effect is removed, the topographical information can be extracted from the phases in interferogram. Now, if the target is moving, then having removed the geometrical effect and the topographical effect, the motion of the target can be measured from the interferogram. ERS tandem data and TerraSAR-X data have been used widely to find the surface velocity of mountain glaciers as well as ice sheets by InSAR method.

5. Comparison between optical, thermal and microwave for Cryospheric studies

The optical remote sensing is based on the detection of reflected solar radiation from surface of the earth in VNIR regions of electromagnetic spectrum which range from 0.4 to 2.5 μm . The basis of TIR remote is the emitted radiation in the spectral range between 8 and 14 μm . Glacier surface has unique spectral properties in the visible-infrared and thermal region, which makes it possible to identify and monitor by optical remote sensing sensors. Optical data at high and

medium spatial resolutions from SPOT5, IKONOS, Quickbird, Landsat TM, ETM+, IRC-1C and ASTER are highly useful for regular monitoring and mapping of glacier. The optical remote sensing is exceedingly of use for temporal change analysis of spatial extent of snow and glacier area. Aided with a DEM, information about the glacier geometry and topography can be obtained from optical data. The thermal bands from satellite data have the potential to distinguish debris cover on the glacier. However, one of the main drawbacks of working in optical remote sensing is their limitation to cloud-free condition and daylight, which are sometimes not possible in mountain region where there are always possibilities of forming cloud due to orographical effects. The active microwave system has the capability of acquiring data at all weather conditions, during any time of the day. The microwave remote sensing is more effectively used in extracting snow properties such as snow depth, snow wetness and SWE and glacier facies mapping. The emerging technologies of InSAR and DInSAR have great potential in deriving glacier volume change, mass balance, surface elevation change and glacier velocity. Thus, for studying the evolution and dynamics of mountain glaciers, the complemented usage of optical, thermal and microwave remote sensing is needed.

6. Glacier hazards

The strong interrelation between climatic changes, glacier recession and increasing number of glacier-related hazards is evident in many mountainous parts of the world including the Alps and the Himalayas [65, 66]. Fundamental changes are taking place rapidly in the high mountain regions due to continued global warming [65]. In consequence to rising temperature and climate change, it is predicted that the existing glaciated may soon transform into new landscape with vegetation sparse-bare lands, loose debris and abundant lakes [65]. Such newly transformed landscape definitely would not be in equilibrium with the ecosystem and would thus cause many hazards in order to balance with the system. The most dangerous glacier-related hazards are formation and growth glacier lakes, glacier lake outburst floods (GLOFs), debris and mud flow triggered by flood, snow/ice/rock avalanches and development of crevasses which pose threat to both life and livelihood and brings devastation to mankind and infrastructure including hydropower [67, 68]. The glacier-related hazards has the potential to cause huge casualties in one single event, the damage amounting to hundreds of million [69]. Thus, the risk of loss of life and the devastation of infrastructure are the main motive for studying glacier-related hazards. Monitoring, assessment and management of glacier-related hazards are highly required for the timely prediction of catastrophes and saving of lives downstream. However, due to remote location, complicated terrain, harsh environment and political restrictions, it is not possible to monitor the mountain glacier-related hazards by field observations. The launching of high-resolution satellites in recent decades, emergence of sensor technologies and development of sophisticated tools have posed remote sensing as effective and efficient alternatives to monitor, assess and manage the mountain glacier-related hazards. The optical spectral region of remote sensing is most suitable for glacier hazards assessment. The nature, characteristics, size and growth of hazards decide the selection of remote sensing data. Fusion of multispectral data with the DEMs is the most promising method of glacier hazards monitoring and assessment. The medium-resolution data from Landsat TM/

ETM+/OLI/TIR, ASTER and IRS LISS III can cover regional- to global-scale hazard assessment, whereas high-resolution data such as Quickbird and IKONOS can contribute in providing detailed information [70]. The geometry of the potential dangerous hazardous sites can be obtained from ASTER DEM, SRTM DEM and DEM from other sources. The geometrical assessment of mountain terrain with the help of DEM can provide information about the potential sites of hazards.

6.1. Glacial lake outburst floods

In response to warming of climate, the increasing number and volume of glacier lakes are raising wide concern. Regular monitoring of supra and pro glacial lakes are the key parameter to identify the glacier lake hazards [71–73]. Most of the glacier lakes form near the snout of the glacier and are dammed by unstable moraines and are called moraine dammed lakes. The enhanced melting of glaciers due to rising temperature amplifies the storage of water in the lakes. This occasionally may lead to the breaching of the moraine dams, releasing huge amount of lake water, which in its course gathers the surrounding debris along with it and cause destruction in the downstream. This phenomenon of flash flood is known as GLOF and is one of the most severe catastrophes to occur in the Alpine and Himalayan regions. Richardson and Reynolds [66] have suggested three mechanism of glacier outburst: the rupture of an internal water pocket, the progressive enlargement of internal drainage channels and catastrophic glacier buoyancy. The term GLOFs is most commonly used for the glacier flash floods of Himalaya. A large number of GLOFs have been recorded in central and eastern Himalaya [67, 74]. Compared to the central and eastern part, the western Himalayas have seen lesser number of GLOFs. The application of modern remote sensing technology to locate and monitor the formation and growth of potentially dangerous lakes is necessary due to their far reach. The glacier dynamics, probability of formation and future development of lakes can be assessed by time series of multispectral images. DEMs are found to be crucial in the assessment of moraine dam characteristics, dam geometry, surface material and geometry. The visual interpretation of time series data have been extensively exploited in the study of glacier fluctuations and glacier lake outburst [75]. Data from Landsat, ASTER, IRS, SPOT, Quickbird and IKONOS can be used for mapping and classification of glacial lakes. The topographical settings of GLOFs can be obtained from ASTER DEM, freely available ASTER GDEM and SRTM DEM [16] with high accuracy level. Huggel and others [75] have proposed an automatic methodology for mapping of Himalayan glacier lakes employing Landsat TM data. The method is known as normalized difference water index (NDWI) and uses TM1 and TM4 for distinguishing the lakes. NDWI is given as

$$NDWI = \frac{TM \text{ bands } 4 - TM \text{ bands } 1}{TM \text{ bands } 4 + TM \text{ bands } 1} \quad (8)$$

In order to calculate the volumetric changes of glaciers, especially the debris-covered type [76], stereo-capable data are useful. The Advanced Land Observing Satellite (ALOS) PRISM is a relatively new remote sensing satellite program (launched in 2006) that has stereo capability

able to generate digital terrain models (DTMs) and 3D maps and that also offers high spatial resolution stereo-data (2.5 m). Several studies have investigated volumetric changes in glaciers in the Himalayas using ALOS data [77]. The estimation of area of potentially dangerous supra and proglacier lake area from remote sensing data can be used to find the glacier volume. The lake volume (V : $\times 10^6 \text{ m}^3$) and lake area (A : km^2) have the following relationship [78]:

$$V = 43.24 \times A^{1.5307} \quad (9)$$

Huggel and others [75] have also represented similar relationships from glacial lakes located in the Swiss Alps, including ice-dammed lakes. The relationship between the maximum depth of lakes (D_{\max} : m) and lake areas can then be calculated as follows [78]:

$$D_{\max} = 95.665 \times A^{0.489} \quad (10)$$

The depth, area and volume of glacier lakes, estimated from remote sensing technology, greatly facilitate in the assessment of GLOFs and maintain the early warning system. Figure 14 demonstrates the continuous growing of a moraine dammed lake located at the snout of Samudra Tapu glacier in Himachal Himalaya, India.

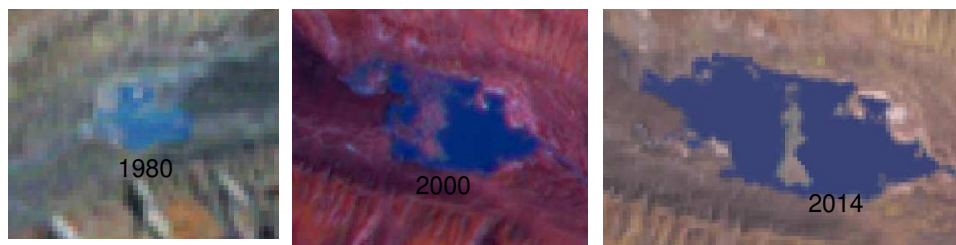


Figure 14. Growth of a moraine dammed lake in western Himalaya as shown using Landsat MSS, IRS LISS III and Landsat OLI/TIRS data of ablation season.

6.2. Snow, Ice and rock avalanches

The hazards associated with debris cover and unstable rock in the glacial environment are crucial to study as they are influenced by glacier down-wasting, glacier retreat and permafrost degradation [37] and are connected with ice avalanches and GLOFs [79]. The increasing number of ice avalanches is basically due to the changes in climatic and socioeconomic settings in the mountain region [12]. Typically an ice avalanche occurs from the surrounding steep cliffs in the glacier environment with the breaking of large mass from these cliffs and peaks. The hazards potential of ice avalanches are confined to the high mountain areas only and affect the tourists, trekkers/climbers and glaciologists. Figure 15 illustrates an avalanche prone steep slope present at the backwall of Hamtah glacier, western Himalaya. The monitoring of

occurrence of ice avalanches and the settings of early warning systems for mitigation require high-quality data and tools for systematic region wide coverage. The combination of GIS tool with the remote sensing data has been found to be useful for hazard mapping in particular to debris flow and snow/ice/rock avalanches. Clague and Evans [80] have demonstrated the use of DEM for comparison of volume of ice avalanched material before and after an event. Salzmann and others [12] have shown that the glacier inventory data can be combined with the slope and aspect maps to locate the potential avalanches zones. The multitemporal data combined with DEMs can be used to identify and monitor the rock avalanches, debris flow and areas to be affected by the debris movement.

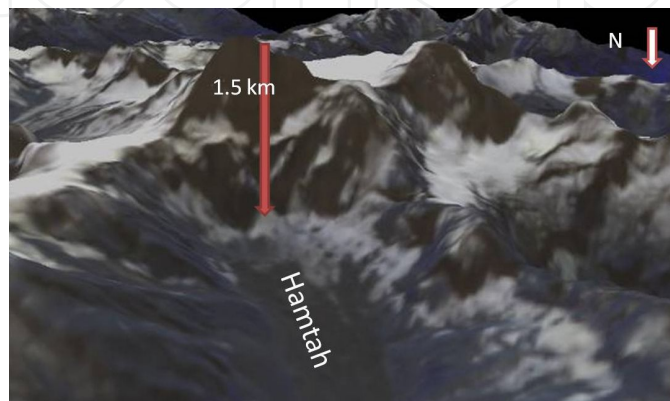


Figure 15. Landsat OLI/TIRS image dated September 28, 2014, overlaid on ASTER GDEM to show the steep back wall and surroundings of Hamtah glacier, which are susceptible to rock and ice avalanches.

6.3. Glacier surges

The glacier surges are abnormally rapid movement of large glacier parts with increased velocity due to the temporal instability of the glacier. The velocity of the glacier increases by an order of magnitude or more during the surging and the glaciers advance drastically. The glacier surges itself are not a hazard, but they induce and trigger other hazards such as ice/rock avalanches, outburst floods, blocking of river, instability of moraines and hence associated hazards. The phenomena of glacier surges are best monitored by high-frequency remote sensing data [81]. A number of glaciers in the Karakoram have been found to be showing the surging phenomena. Bhambri and others [81] have studied the surge type behavior of glaciers in Karakoram by using CORONA, Landsat TM/ETM+ data and SRTM DEM.

7. Conclusion

Glaciers are the most visible indicators of climate change, and the study of glacier parameters specifies the prevailing climate. The numbers of glaciological parameters which can be assessed and monitored by remote sensing technology are very long. The optical and radar data are equally valuable and useful for snow cover mapping, glacier area monitoring, glacier feature study, volumetric change, mass balance and velocity measurements. Optical remote

sensing data is more suitable for snow cover mapping, glacier area and snout monitoring. However, glacier facies mapping, mass balance and glacier velocity can be accurately studied from radar data. DEMs are the essential requirement for studying glacier topographical and geometrical parameters. Although remote sensing methods provide an efficient tool for glacier study, the field method is the most accurate and recommended one, and remote sensing should be applied in conjunction with field work for validation.

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