CHANGE MONITORING OF GANGOTRI GLACIER USING SATELLITE IMAGERY

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Abstract:

The Himalayas possess one of the largest concentrations of glaciers outside the Polar Regions, which act as a huge potable water reservoir. The mountain ranges of the Himalayas stretch for a distance of about 2,400 kilometers from east to west direction in the shape of an arc along the northern border of India covering an area of about 500,000 square kilometers. Monitoring the glaciers is important for environmental observation. This paper presents the results obtained from the analysis of a set of multitemporal Landsat images for the study of the status of the Gangotri glacier. Satellite data of Landsat 1972, 1976, 1990, 2000 and 2010 are used in the investigation. The investigation has shown an overall reduction in glacier area from 169.186 sq. km in 1972 to 156.587 sq. km at present, an overall deglaciation of more than 7%. The accumulation area decrease 25% from 76.158 sq. km in 1972 to 56.909 sq. km in 2010, on the other hand ablation area increase 7% from 93.028 sq. km in 1972 to 99.678 in 2010. The AAR was also estimated by using Landsat MSS, TM and ETM+ images which can be useful in obtaining a trend in mass balance for Gangotri glacier. The mass balance of the Gangotri glacier is estimated using Accumulation Area Ratio method for the year 1972 is – 10.808 cm. where as in 2010 it is -31.87166.

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Index Terms—AAR, Mass Balance, Accumulation Area, Glacial Extent

Introduction

The Himalaya comprise one of the largest collections of glaciers outside the polar regions, with a total glacier cover of 33 000 km^2 [1] and around 9600 glaciers exists in the Indian Himalaya [2]. Himalayan glaciers are the important source of fresh water for the innumerable rivers that flow across the Indo-Gangetic plains. The rivers flow trans-boundary and meet the potable water, irrigation, hydropower, fishery, inland navigation and other needs of more than 1.3 billion people living downstream. With about 9,575 small and large glaciers in the Himalayas [3], they hold the largest reserves of water in the form of ice and snow outside the Polar Regions [4]. The Himalayas are thus also referred to as the 'water towers' of Asia and a 'third pole' of the earth.

Monitoring of glaciers actuates scientific interest for two main reasons. First, Glaciers change monitoring has been used for climatic change investigation. The surface area and volume of individual glaciers are monitored to estimate future water availability. Second, glaciers in Indian Himalayas, have been recognized as important water storage systems for municipal, industrial and hydroelectric power generation purposes. The use of mountain glaciers as a climatic indicator requires an assessment of the complex parameters as Accumulation Area Ratio(AAR) and mass balance and glacier area change. The mass balance of a glacier reflects the relation between glacial characteristics climate change and mass balance of a glacier is measured to calculate the volume of glacier. The mass balance of a glacier can be extracted by glaciological methods. Glaciological methods used by drilling into the ice and installing stakes in the ablation zone to know the amount of Melting ice , a pit is also install in the accumulation zone to measure the yearly input of snow. However using these conventional methods monitoring of Himalayan glaciers is normally difficult due to the rugged and inaccessible terrain and also larger number of glaciers. Therefore, field-based records have been made at selected Himalayan glaciers. This may not provide a complete and representative scenario of glacial retreat. The use of remote sensing techniques is of great relevance and importance particularly for studying glacier large number of inaccessible glaciers. Recent advances in satellite technology have enabled us to measure glacial, accumulation area ratio (AAR) and equilibrium-line-altitude (ELA) and volume of glacier can be estimated using various approximate methods. In this scenario, Accumulation Area Ratio(AAR) and equilibrium-line-altitude methods are discussed in this paper to find out the mass balance of different years.The Landsat satellite MSS, TM5, and ETM+ images were used to get AAR values for the years 1972, 1976, 1990, 2000 and 2010. [5] Developed a relationship to estimate the approximate depth of glacier and this relationship used by [6]. [7] Developed a relationship used to estimate mass balance from Accumulation area Ratio (AAR). [6] Estimated mass balance of Parbati glacier using same relationship developed by [7]. [6] Provide an inventory of glaciers in the Parbati, Baspa and Chenab using Survey of India topographic maps prepared in 1962, LISS-III and LISS IV Satellite images. Glacier area were mapped from 1962 to 2004 and volume estimated for same duration. Several mapping and monitoring studies exist for Gangotri Glacier, the largest glacier in the Garhwal Himalaya [8] and [9] and a few studies have been published on mapping and variability of selected glaciers of the adjacent Saraswati/Alaknanda basin e.g. [10].

In our current investigation all parameters such as depth, mass balance, and volume are derived by the geodetic equations on the basis of glacial extent, therefore mapping total glacial area, accumulation area and ablation area was very crucial. We used **ESRI Arc GIS 9.3** for mapping these glacial features.

Study Area

Gangotri Glacier originates in the Chaukhamba massif (6853–7138 m a.s.l.) and flows northwest towards Gaumukh. The equilibrium-line altitude (ELA) of Gangotri Glacier is 4875 m a.s.l. [11].The Gangotri glacier, one of the largest ice bodies in the Garhwal Himalayas, is located in the Uttarkashi district of the state of Uttarakhand in India (See Fig 1). It is one of the most sacred shrines in India, with immense religious significance. Being the main source of the river Ganga, it attracts thousands of pilgrims every year. The Gangotri glacier is a vital source of freshwater storage and water supply, especially during the summer season for a large human population living downstream. The discharge from the glacier flows as the river Bhagirathi initially before meeting the Alaknanda River at Devprayag to form the river Ganga. Snow and glaciers contribute about 29% to the annual flows of the Ganga (up to Devprayag) and hence any impacts on these glaciers are likely to affect this large river system [3]**.**Numerous smaller glaciers join the main stream of the main glacier to form the Gangotri group of glaciers. The study area is Gangotri glacier including it tributary glaciers such as Maidani Glacier Swachand glacier, Sumeru Glacier, Ghanohim Glacier and Kriti Glacier system. For ease in writing we abbreviated these all tributary glacier as Gangotri Glacier System in this investigation.

This system covers an area of 156.587 sq km (ETM+2010).The area of the main trunk of the glacier 62.412 sq km [12], Average width of the glacier is 1.847 km and glacier, lies between 79°4’ 46.13” E-79°16’ 9.45” E and 30°43’ 47.00” N-30°55’ 51.05” N (ETM+2000). It has varying elevation of 4082–6351 meters above sea level (SRTM Data Analysis)

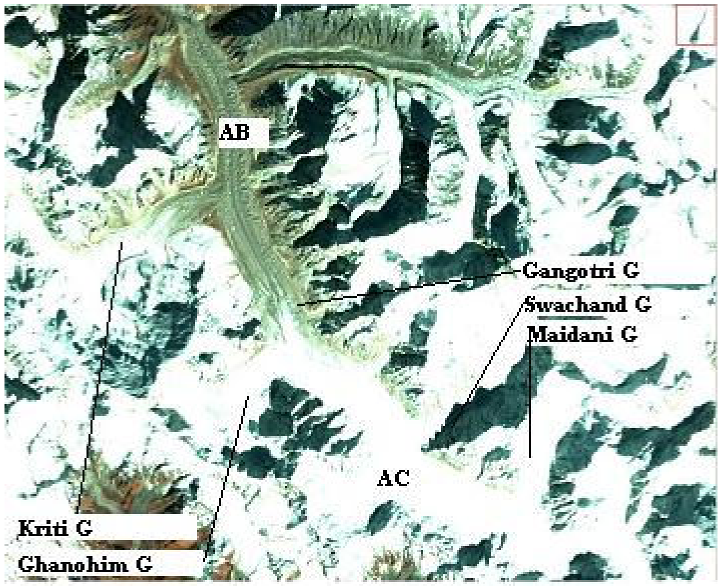

Fig. 1. False Color Composite (FCC) of RED (4) Green (3) Blue (2) in the Gangotri Glacier, Subset of Landsat-7 ETM+ Image(G=Glacier, AB= Ablation zone and AC= Accumulation Zone).

Data Sources

The multi-spectral satellite data of Landsat MSS for the year 1972 and 1976, Landsat TM5 data for 1990, Landsat ETM+ data for the years 2000 and 2010 have been procured in the present study (see table 1). The Landsat data used in current investigation system was downloaded for free from the USGS Global Visualization Viewer (GLOVIS).

Table-1 Details of Satellite data used in the analysis

Satellite Data	Date of acquisition	Spatial resolution (m)
Landsat MSS	26/10/1972	79
Landsat MSS	19/11/1976	79
Landsat TM 5	21/10/1990	30
Landsat ETM+	25/05/2000	30
Landsat ETM+	13/11/2010	30

Glacier mapping was undertaken employing digital elevation models (DEMs) i.e. ASTER and SRTM DEM freely downloaded from ASTER GDEM and US Earth Explorer. In this we investigation we find out that elevation values from ASTER DEM are higher than SRTM DEM. However SRTM DEM looking smoother but problematic at moraines.

Methodology

The spatial-based detection of variations in glacial extent requires co-registration of multi-temporal images with one another, a task easily achievable in GIS. GIS is an efficient tool for analyzing current state and changes in glaciers (Li et al., 1998). Other analyses such as classification and detection can also be carried out in GIS, as can measure the glacier area and change in glacier termini. A database within a GIS may be manipulated to yield information on changes in glacier size.

For Landsat MSS data

In this study, a Landsat MSS imagery of Oct 1972 and Nov 1976 covering the Gangotri glacier system was downloaded for free from the USGS Global Visualization Viewer (GLOVIS). The main glacier body is almost cloud free. The terrain of Himalayan glaciers has undulating surface and steep slopes, so the radiance reaching the sensor greatly depends on the orientation (slope and aspect) of the target. The incoming radiance is highly depend on the orientation of the object Therefore, for better recognition of the classes for effective mapping, the DN numbers have to be converted into topographically corrected reflectance images. AAR Estimation requires mapping of glacier extent and accumulation area, Therefore to get accumulation area classification was required so in a second step, both supervised and unsupervised classification are performed to extract four classes rock, snow, ice and debris ice. In third step accumulation area and total glacier area has been measured by visual demarcation and GIS techniques using ArcGIS 9.3.

For Landsat TM and ETM+ data

Earlier studies have shown that normalized-difference snow index (NDSI) and band ratio methods could not differentiate debris covered glacier ice from surrounding rock surface due to similar spectral signatures[14], However, when compared with manual delineation, thresholding of NDSI and band ratio methods are better approaches for mapping clean glacier ice [14]. It has been reported that for shaded areas with thin debris cover the band ratio near-infrared/ shortwave infrared (NIR/SWIR) performs better than red/ SWIR and NDSI [16]. In our study, several image band ratios (1/3; 3/ 4), NDSI (1–4/1+4) and classifications were tested using Landsat imagery. Band ratio NIR/SWIR was most suitable for mapping clean glacier ice. Ratio images have been successfully used for the delineation of glaciers for the Swiss Glacier Inventory (SGI) and a study in the Inner Tien Shan [16].

In a first step, TM4/TM5 ratio images were calculated and segmented using a threshold value of 1 using raster math tool in ArcGIS 9.3. Using Image enhancement techniques snow and snow free area classified easily. Ratio Images was associated with ASTER Digital Elevation Model for mapping glacial extent and accumulation area using visual demarcation. One major problem in mapping glacier is related to the exact definition of glacier, whether ‘inactive’ bodies of ice above a bergschrund connected to a glacier should be considered as part of the glacier. Currently, there is no consensus within the glaciological community on these issues. For example, some previous studies (e.g. 15) excluded the inactive parts at the heads of glaciers, so concerning that problem we generated surface slope image from ASTER DEM using Terrain and TIN surface tool. Now we overlay delineated area of glacier extent derived from ratio image and surface slope image. Accumulation area, ablation area and total area of glacier was measured much accurately and misclassified pixels of peaks and rocky surface are eliminated. ESRI ArcScene was used for visualization of glacial extent image with digital elevation model.

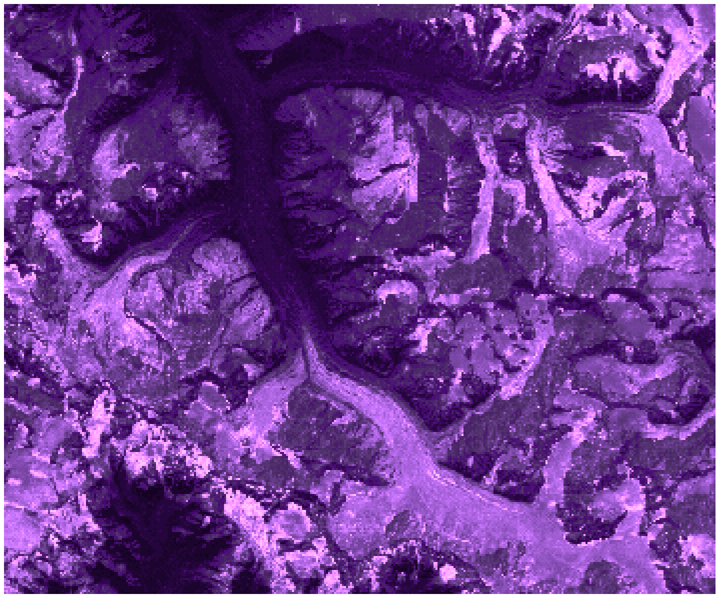

Fig. 2 Ratio Image TM4/TM5 segmented and threshold of value 1(attributed).

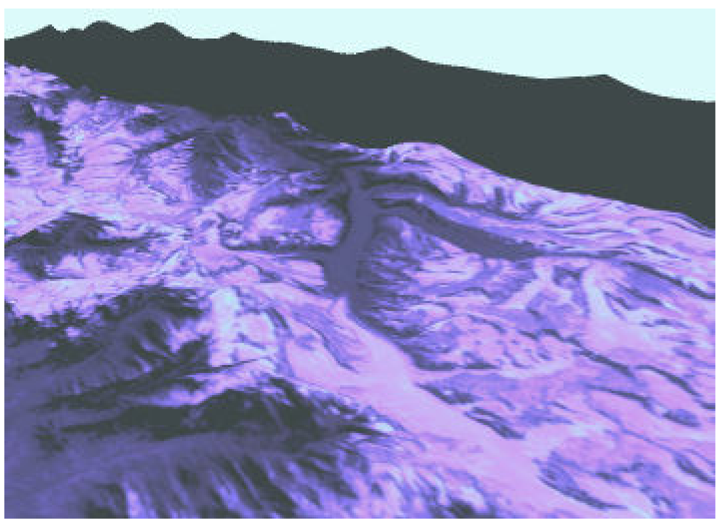

Fig. 3. TM4/TM5 Ratio Image associated with DEM

AAR is a ratio between accumulation area and total glacier area [16]. Accumulation area is the area of a glacier above the equilibrium line. In temperate glaciers, the extent of superimposed-ice zone is insignificant and therefore, the equilibrium-line coincides with the snowline [18]. Snow-line at the end of the ablation season and AAR can be estimated using remote sensing method applied by [7]. Volume of water stored in glacier can be estimated using various approximate methods.

[5] Developed a specific relationship between glacier area and depth has been developed for the Himalayan glaciers.

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

Where H is the mean glacier depth (m) and F is the glacier area (sq. km).

This depth information is used with glacial extent derived from the overlay of surface slope and ratio image. Now using surface volume tool of ESRI ArcGIS 9.3 we derived the volumes of observation years.

Glacial mass balance was estimated using Accumulation Area Ratio (AAR). [6] Developed the following relationship was used to estimate mass balance from AAR.

$$b = 243.01*X - 120.187$$

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

Since these two relationships has been used to estimate depth, mass balance and volume of Gangotri glacier between 1972 and 2010.

Results and Discussions

The Gangotri glacier is one of the largest glaciers in the Himalayas. Numerous small sized glaciers also join the main Gangotri glacier from all sides and form the Gangotri group of glaciers. The main glaciers as well as its tributaries are valley glaciers .The total ice cover is approximately 156.587 km^2 and estimated volume of ice is 36.17 km^3. The area and length of the main trunk of the glacier is 62.412 sq km and 29.38 km respectively [12]. The average width of the glacier is 1.85 km. The glacier, lies between 79°4′ 46.17″ E-79°16′ 10″ E and 30°43′ 46.98″ N-30°55′ 50.96″ N (ETM+2000). It has elevation range from 4,017–6,146 meters above sea level (SRTM data analysis).

Table 2-Measured and estimated characteristics of Gangotri Glacier

Year	Total Area(Sq. km)	Accumulation Area(Sq. km)	Ablation Area(Sq. km)	Depth(m)	AAR	Mass Balance(cm)	Volume(Km^3)
1972	169.186	76.158	93.028	236.7090	0.4501	-10.808199	40.047848874
1976	168.858	75.419	93.439	236.5647	0.4464	-11.658734	39.945723912
1990	162.458	67.233	95.225	233.7079	0.4138	-19.620462	37.967571806
2000	159.136	60.342	98.794	232.19391	0.3791	-28.061909	36.950265248
2010	156.587	56.909	99.678	231.01713	0.3634	-31.87166	36.1742746377

Table 3- Elevation and topographic analysis of Gangotri Glacier

Characteristics of Gangotri Glacier	ASTER DEM Analysis	SRTM DEM analysis
Min altitude	4101	4082
Max altitude	6389	6351
ELA	4684	4649
Relief	2288	2269
Aspect	NW	NW
Slope	5.15^0	5.61^0

In this we investigation we find out that elevation values from ASTER DEM are higher than SRTM DEM, However SRTM DEM looking smoother but problematic at moraines. Glacier mapping using a TM4/TM5-ratio image in combination with a DEM was successfully performed and the accumulation area, ablation area and total area of Gangotri along with TG's (Maidani Glacier, Swachand glacier, Sumeru Glacier, Ghanohim Glacier and Kriti Glacier).

Most of the glacier change studies from the Indian Himalaya are based on a comparison of satellite data with 1960s topographic maps. However, several studies have reported that mapping of glacier areas on Survey of India (SOI) topographical maps has serious accuracy issues [19 and 2].Loss in main trunk of glacier area was estimated using high and medium resolution of Landsat ETM+ and MSS data .In this investigation, glacial area loss from 1972 to 2010 was estimated. The investigation has shown an overall reduction in glacier area from 169.186sq km to 156.587 sq km between 1972 and 2010, an overall deglaciation of 7.44% percent.

Using Remote sensing AAR and total area and accumulation area is measured by Landsat Imagery of 1972, 1976,1990,2000,2010. Following the approach of Chahoi et al. (1988), glacier depth was estimated using glacial extent. Once depth is estimated then volume for different years was derived. The relationship given by Kulkarni et al (2004) used in current investigation to estimate the mass balance of Gangotri glacier. For those glaciers, where historical data either not available or measurement using direct glaciological methods not possible due to large number of glaciers, in both cases Remote sensing can play a significant role. In case of Himalayan glaciers where field data are available for limited number of Glaciers, The AAR value for thousands of Himalayan glaciers can be obtained by using satellite images.

Conclusion

The recent advent of Geographic Information Systems (GIS) and Remote sensing techniques have created an effective means by which the acquired data are analyzed for the effective monitoring and mapping of temporal dynamics of glaciers. Longitudinal variations in glacial extent have been detected from multi-temporal images in GIS. A large number of researchers have taken advantage of remote sensing, GIS and GPS in their studies of glaciers. In this study, accumulation area, ablation area and total glacial extent of Gangotri Glacier with TG's (Maidani Glacier, Swachand glacier, Sumeru Glacier, Ghanohim Glacier and Kriti Glacier) mapped using ratio images with the association of surface slope. This study shows that the mass balance and glacier volume can be estimated using combination of GIS and remote sensing techniques. The mass balance study using remote sensing is good for monitoring a larger area and the glacier those are difficult to access.

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