Remote Sensing and GIS Analysis of Gaumukh Snout Retreat and Ice Loss Estimation at Gangotri Glacier, During 1962-2015

Parthapratim Ghosh
Department of Geology, Banaras Hindu University, Varanasi 221005, India.

Abstract
The recession of snout of Gangotri Glacier has been a concern to many glaciologists and environmentalists around the world. The recession is continuous and at alarming rate. The present study is an attempt to make comprehendible thought about the actual recession over Gangotri glacier using multispetsral and multi temporal LANDSAT images 2015 and with the help of a toposheet of the Gangotri glacier of 1962. The investigation has shown the loss of the ice volume in the snout area, the Gaumukh of the Gangotri glacier has increased from 6.4 million cubic meters in between 1780 – 1962 to 7.71 million cubic meters in between 1962 – 2016. The average annual rate of the loss of the ice volume in the snout area also has been increase from 37,100 cubic meters in between 1780 – 1962 to 142,852 cubic meters per year during 1962-2015. Knowledge of the volumetric reduction of the glacier area is essential for the hazard mitigation and management in Himalayan environments where glaciers are presently retreating and are likely to retreat in the near future if global warming occurs. This retreat may be due to direct or indirect effects of climate change and may be caused largely by human activity and may be due to other anthropogenic activities.

Keywords: Gangotri glacier, snout recession, Landsat, ice volume loss.

Introduction
The Himalayan region has one of the largest concentrations of glaciers and large areas of the Himalayan mountain range are also covered by snow during winter. Therefore, this region is also known as the ‘Third Pole’. Many major rivers and their numerous tributaries originate from these snow and glacier-bound regions. Meltwater from snow and glaciers makes these Himalayan rivers perennial, and has helped in the flourishing of several civilizations along the banks of these rivers for ages. However, this source of water ought not to be considered permanent, as the geological history of the Earth suggests constant variations in glacial extent due to change in climate. Moreover, natural changes in the climate would have altered due to greenhouse effect caused by manmade changes in the Earth’s environment (Puri and Shukla 1995).

Gangotri Glacier is the largest glacier (length ~ 30 km) in the Garhwal Himalayas. The Bhagirathi River originates from the snout (Gaumukh; ~ 3950 m asl) of Gangotri Glacier, which is the main source stream of Ganga River. Gangotri Glacier originates from the Chaukhamba group of peaks (~ 6853–7138 m) and flows northwest towards Gaumukh. About 29% of its total area is covered by debris (Jangpangi, 1958, Zemp et al., 2008, Vishal, 2016). Gangotri Glacier is one of the well documented and monitored glaciers in the Indian Himalayas as regards to its snout position. The snout of Gangotri Glacier is very commonly known as Gaumukh (the mouth of cow). The Gangotri Glacier system is a cluster of many glaciers comprising the main Gangotri Glacier (length: 30.20 km; width: 0.20 - 2.35 km; area: 86.32 km2) as the trunk part of the system. The melt-water stream emerging from the snout of the Gangotri Glacier at an elevation of 4000 m is known as Bhagirathi River. The Gangotri Glacier is a valley glacier with a cluster of tributary glacier systems (Figure 1).

In the era of global warming as like other Himalayan glaciers, Gangotri Glacier is also melting and retreating at a particular rate. Recently, there have been news and discussions that the Gangotri Glacier is melting at a rapid rate and it is likely that it will disappear in the next 20–30 years. Fears are been expressed that its disappearance will lead to a dry Ganga, which will not only jeopardize the life of more than 50 crore people, but also seriously hurt the religious sentiments of many more. This note presents a broad analysis of the flow contribution of major tributaries to the flow of the Ganga as well as the likely impact of the Gangotri Glacier melt on the quantity of flow in this river at various locations. Auden in 1935 first mapped the location of snout and after that several scientists from GSI have mapped the position of snout. The Gangotri Glacier in the past had extended up to the Sukhi, below Jhala (40.5 km downstream of Gaumukh) in Bhagirathi valley, as indicated by the remnants of moraine. This is the oldest terminal moraine of this glacier and its position probably represents the position of the snout during Pleistocene. This resulted in the expansion of the glaciered area in the form of a long valley glacier system covering a minimum area of 685 sq. km, during Bhagirathi glacial stage, 105 years ago (Sharma 1996). The most extensive landform, either in the form of the relicts of Pleistocene or the present glacial deposition in
various forms is frequently encountered in this valley. The past Corona Imagery (Figure 2) shows the retreat signatures of the Gangotri Glacier.

![Location of Gangotri Glacier with its tributary glaciers](image1)

**Fig 1:** Location of Gangotri Glacier with its tributary glaciers (Modified after Bhamri et al. 2011)

The snout of the glacier “Gaumukh” is about 18 Km from the holy shrine of Gangotri. The glacier snout has been under the state of continuous recession since 1935 (Auden, 1937). GSI has monitored snout of the glacier since 1935 till 1996. The data reveal that the glacier has retreated by 1147 m, with an average rate of 19 m/year between 1935 and 1996. The total area vacated by the glacier

![Retreat Signature of Gangotri Glacier](image2)

**Fig 2:** Retreat Signature of Gangotri Glacier (After Auden and Vohra)
In the past, many workers have been carried out extensive works to measure the linear retreat length and rate for the Gangotri Glacier i.e. how many meters or kilometers of length it had retreated backwards due to melting of glacier. In the present study an attempt has been made to measure and estimate the loss of ice volume by taking into consideration the depth of Gangotri Glacier as well. Being a valley glacier the cross-section is like a triangle and using the length factor a total loss of ice has been estimated.

**Materials and methods**

**Study Area**

Gangotri glacier originating from Chaukhamba peaks (7138 m asl) is 30.2 Km long with a glaciated area of about 143.58 Km². The present day snout is more than 18 km from Gangotri township. Gangotri glacier is one of the most important glaciers in Central Himalaya which is the source of the river Bhagirathi, the largest tributary of Ganges, emanating from the Gangotri group of glaciers in Uttarkashi district of Uttarakhand (Figure 3). The other major tributary Alaknanda emanating from the Satopanth and Bhagirathi glaciers north of Badrinath in Chamoli district of Uttrakhand meet at Devprayag and give rise to Ganga river, which is the most important source of fresh water supporting the population of north Indian Himalaya and plains.

**Geology of the study area**

It is a valley-type glacier, situated in the Uttarkashi district of Garhwal Himalaya, Uttarakhand and it flows towards NW direction. This glacier is bound by between 30°43'22"–30°55'49" (lat) and 79°4’41"–79°16’34" (long), extending in height from 4120 to 7000 m.a.s.l but the studied area of the glacier is in between 30°50’–31°0’ (lat) and 79°0’–79°10’ (long). This area is situated north of the Main Central Thrust (MCT) and is made up of bedrocks of granites, garnet mica schist, quartz biotite schist, kyanite schist, augen gneiss and banded augen gneiss (Naithani et al. 2001). The granitic rocks of Gangotri-Gaumukh area form part of the Badrinath Granitoid. The granite granodiorite body to its south has high grade metamorphites with biotite as the dominant mafic of early Ordovician, but towards northeast the rocks of the Tethyan basin are exposed. It is a medium grained, crudely foliated, S-type, 2-mica granodiorite which is emplaced syn-Caledonian orogeny, consists of xenoliths of schist, termolite-actinolite rocks and fine grained greyish granite. It is intruded by leucocratic tourmaline granite of Miocene age, besides still younger numerous pegmatite, aplite and quartz veins (Bassi, 2004).The glacier is composed of a variety of depositional features such as talus cones, snow avalanche fans, snow bridges, and dead ice mounds, and erosional features like pyramidal and conical peaks, serrated ridge crests, glacial troughs, smooth rock walls, crags and tails, waterfalls, rock basins, gullies and glacial lakes. All along the Gangotri Glacier, several longitudinal and transverse crevasses are formed along which ice blocks have broken down. The ablation zone of the Gangotri Glacier is covered by a thick pile of supraglacial moraines and is characterized by several ice sections, melting into pools of supraglacial lakes. Because of subsidence and the fast degenerating nature of the glacier, its center is full of supraglacial lakes. In this part of higher Himalaya, glacial melt water dominates the fluvial system.

**Methodology**

A general remote sensing and GIS approach have been taken into consideration for this particular study. Firstly, the Survey of India topsheets of year 1962 in 1:50,000 scale were acquired. After georeferencing of the topsheets, theme contour was digitized. From those digitized contours Digital Elevation Model (DEM) was prepared. From the DEM a prime derivative of it Shaded Relief Model.
(SRM) or Hillshade was prepared. Hillshade shows the true relief perception of the area. Six profile lines were drawn in Arc GIS 10 among which three across the glacier and three across the river. The profiles of the valley are showing a V-shaped pattern.

Landsat 8 ETM+ standard FCC was prepared which is of 30 m spatial resolution. From the past records and literatures several retreat signatures have been marked on the satellite image in ERDAS Imagine 2015 software. Over the newly acquired FCC the latest snout position has also been marked along with the other past locations of retreating Gaumukh snout. After that the width and depth of the valley were measured. The valley shape being the triangular V the area of the profile was calculated using trigonometric formula and from the length of retreat the total volume of ice lost was estimated. Apart from this the average rate of ice volume loss was also determined.

Results and Discussions
A composite Remote Sensing and GIS approach has been taken into consideration for the present study. The concept has been developed by considering the valley shape as V. The DEM shows the variation of depth in the Gangotri Glacier (Figure 4) in which the white colour is the valley and yellow and dark brown colours are the ridges.

Six profile sections were drawn over the hillshade, three over the glacial ice and three over the river valley at nearly same distance intervals (Figure 5). The results of six profile graphs are showing the valley profiles under ice and water in 1962 (Figure 6).
Fig 6: Valley profiles showing in profile graphs drawn on Hillshade.

To calculate the area of the profile graph a simple trigonometric formula has been used. The area of a triangle is:

\[
\frac{1}{2} \times \text{Base} \times \text{Height}
\]

Determination of the valley-depth and valley-width with the help of the profile graph

With the help of measurement system, a scale has been determined of the profile graph and the depth and width of the valley has been measured subsequently. For all the measurements, the profile graph which have used are profile graph 1(ice), profile graph 2(ice) and
profile graph 3(ice). All the three measurements were taken. For the calculation of the volume loss, calculation of the area of the ice sheet which was determined by the formula of the area of the triangle:

\[
\text{Area of the ice sheet} = \frac{1}{2} \times (\text{ice width}) \times (\text{ice depth})
\]

Here, the valley-shape is of course assumed as the shape of the triangle and above formula has been used for the calculation and also the valley-width and valley-depth are assumed constant throughout from 1962 to 2015. The depth and the width of the valley at the snout position have been measured as 40m and 261m respectively. So, the according to the formula used, the area will be 5320 sq. m. There might be some measurement and calculation errors but the approximate area value of the obtained result was taken.

Estimation of the volume loss concerned with the change in valley – length in the time period of 1962 – 2015 at the snout area, the Gaumukh:

The change in valley length for the mentioned period has been measured with the help of the FCC (False color composite) of the LANDSAT 8 image data (Figure 7). The location of snout at the toposheet (in 1962) and the location of snout shown in satellite image (in 2015) were measured. Using the scale the retreat of snout was determined. The measured value has been multiplied by the above calculated value for the estimation of the volume loss. So, the change in valley – length in 54 years during 1962 – 2015 is 1450m. The loss of ice volume will be 7,714,000 cubic meter, i.e. 7.71 million cubic meter.

![Fig 7: The current position of Gaumukh snout determined from the satellite image.](image)

The estimated volume loss has been averaged per annum for the 54 years (1962 - 2015). And, it is 142,852 cubic meter per annum, i.e. 0.14 million cubic meter per annum. In the present study some very important results has been found. As the focused study area was the snout area, the Gaumukh of the Gangotri Glacier and, the time period for the study of has been taken from 1962 (as the toposheet of Gangotri glacier was of 1962) to the current time 2015, the results are as following:

1. The receded length of the ice position at the snout is 1450m for the time period of 1962 – 2015.
2. The volumetric loss of ice (the loss of the volume of ice) at the snout area, the Gaumukh, is 7,714,000 cubic meter i.e. 7.71 million cubic meter during the time period of 1962 – 2015.
3. The average annum rate of the volumetric loss of ice per year for the time duration of 54 years from 1962 – 2015 at the snout area, the Gaumukh, is 142,852 cubic meter per annum, i.e. 0.14 Million cubic meter per annum.

As now results are shown, so these data can be compared to the previous situation of ice position at the snout place of the Gaumukh. Data are available for the same parameter which has underlined above for the time period of 1780 – 1962 (almost time duration of 184 years). So, for the above mentioned time period, the data are as following:

1) The receded length of the ice position at the snout is 1214m for the time period of 1780 – 1962.
2) The volumetric loss of ice (the loss of the volume of ice) at the snout area, the Gaumukh, is 6,458,480 cubic meter i.e. 6.4 million cubic meter during the time period of 1780 – 1962.
3) The average annum rate of the volumetric loss of ice per year for the time duration of 184 years from 1780 – 1962 at the snout area, the Gaumukh, of the Gangotri glacier is 35,100 cubic meter per annum i.e. 0.03 million cubic meter per annum.

The investigation has shown the loss of the ice volume in the snout area, the Gaumukh of the Gangotri Glacier has increased from 6.4 million cubic meters in between 1780 – 1962 to 7.71 million cubic meters in between 1962 – 2015. And, the average rate of the loss of the ice volume per year in the snout area also has been increase from 37,100 cubic meters in between 1780 – 1962 to 142,852 cubic meters (Table 1).
Table 1: Comparative Ice volume loss during 1780-1962 and 1962-2015.

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<tbody>
<tr>
<td>Time Duration (Years)</td>
<td>184</td>
<td>54</td>
</tr>
<tr>
<td>Receded Length at Snout (m)</td>
<td>1214</td>
<td>1450</td>
</tr>
<tr>
<td>The loss of ice volume in the snout area (in cubic meter)</td>
<td>6.4 Million</td>
<td>7.71 Million</td>
</tr>
<tr>
<td>The average rate of the loss of ice volume at the snout area (in cubic meter per annum)</td>
<td>35,100</td>
<td>142,852</td>
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<tr>
<td>The loss of the of ice volume and the average annum rate of the loss of ice volume as qualitative</td>
<td>Less</td>
<td>More</td>
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So, why there is more loss of ice volume in 1962 – 2016 in comparison to 1780 – 1962. It can be explained with the facts that since it is an interglacial period and the current Holocene interglacial began at the end of the Pleistocene, about 11,700 years ago. So, in the current time there is a minimum occurrence of the advancement of the ice sheet. But there is an important phenomenon which took place some hundreds of years ago. In the period of 1550 – 1850, there was little ice age, and in between 1650 – 1850, there was much glaciations and ice advancement in comparison to last 150 years. So, it is quite obvious about more retreat of ice volume during 1962 – 2015.

In addition to that there are also some more contributing factors that can be attributed to the facts of retreat of the glacier like increased human population, anthropogenic activities like pilgrimage and associated construction work, expedition and other adventure related sports activities and also the most important green house gas emissions. All of these ultimately lead to the global warming phenomenon which is massively hazardous for the health of the glacier.

Conclusion
Attempts have been made to explore a comprehensive database on the snout position (Gaumukh) of the Gangotri glacier with particular reference to the environmental impacts. Studies on the volumetric analysis of the loss of the ice volume and the average rate of the volume loss per annum of the snout concerned about Gangotri Glacier has shown that the snout of the Gangotri Glacier has been retreated 1.45 km in last 54 years. The investigation has shown the loss of the ice volume in the snout area, the Gaumukh of the Gangotri Glacier has increased from 6.4 million cubic meters in between 1780 – 1962 to 7.71 million cubic meters in between 1962 – 2016. And, the average rate of the loss of the ice volume in the snout area also has increased from 37,100 cubic meters in between 1780 – 1962 to 142,852 cubic meters. In other words, the melting rate of the ice volume of the glacier is much higher than the accumulation rate of the ice and it is common situation for the most of the glaciers of the world. It could be much destructive to the local surroundings and can bring catastrophic changes on the earth surfaces. It may be because of many causative factors like high solar activity, green house gas emission, increased human population and their activities, atmospheric changes due to global warming, etc.

References
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