This is an evidence of the calcium sensing mechanism present in the leaf. The size, morphology and ratio of COM depend on the type of leaf used as template. Spherical COM particles (40–70 nm) were obtained from reactions in the presence of *H. adenophyllum* leaves, whereas spinach leaves led to the formation of aligned nanostructures consisting of spherical particles of diameter of 100–150 nm.

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A comparative study of deglaciation in two neighbouring basins (Warwan and Bhut) of Western Himalaya

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Glaciers of the Himalaya contribute significantly in the processes linking atmosphere, biosphere and hydrosphere, thus need to be monitored in view of the climatic variations. In this direction, many studies have been carried out during the last two decades and satellite-based multispectral data have been used extensively for this purpose throughout the world. The present study is aimed at mapping of glaciers in two adjacent basins (Warwan and Bhut) of the Western Himalaya with almost similar altitude and latitude and comparing the changes in the two time-frames with respect to three parameters, i.e. area, debris cover and area–altitude distribution of glaciers. The two time-frames are topographical maps of 1962 and IRS LISS III images of 2001/02. Deglaciation was observed in both the basins with 19% and 9% loss in the glaciated area in Warwan and Bhut respectively. This difference may be due to: (i) the smaller size of the glaciers of the Warwan Basin (e.g. 164 glaciers having < 1 sq. km area in comparison to 101 glaciers in the Bhut Basin), (ii) lower percentage of moraine cover in Warwan (18) than in the Bhut Basin (30) and (iii) higher percentage of glaciated area lying below 5100 m (80) in Warwan than in the Bhut Basin (70).

Keywords: Bhut, deglaciation, glacier, Warwan.

GLACIERS of the Himalaya contribute significantly to the processes linking atmosphere, biosphere and hydrosphere. The processes are realized through: (i) occurrence of high albedo from the snow and glacier cover; (ii) perennial flow of freshwater to all the rivers originating in the mountainous region; (iii) variation of glacier extent with respect to climate change, thus acting as sensitive indicators; (iv) percolation of melt water to groundwater storage in the mountains; (v) transportation of enormous sediment load; (vi) reshaping the peri-glacial geomorphology and (vii) maintaining and regulating the weather pattern through the frozen state. The water resource produced by the melting of snow and glaciers of the Himalaya has sustained a large population since historical times (currently almost 800 million people) living in the

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Himalayan mountains and along the Indo-Gangetic alluvial plains[1,2].

In view of the aforementioned reasons, it is imperative to study dynamics of the Himalayan glaciers with respect to scenarios of climate change. In this direction many studies have been carried out during the last two decades on the fluctuations of Himalayan glaciers. The studies have been based on either comparison of glacier extent extracted from satellite images acquired in the optical region for extraction of glacier features and extent as shown in topographical maps published by the Survey of India (SOI)[3–8] or field studies carried out during glacial expeditions[9–11]. The use of satellite images for studying glacier fluctuations has a greater advantage over conventional methods as it saves time and effort because a large number of glaciers can be periodically viewed together due to synoptic view.

Meanwhile, some authors have argued for adopting glacial extent from topographical maps, as it is believed that these maps were prepared from aerial photographs acquired in winter[12]. However, there are no published reports on the time of acquisition of aerial photographs from which the maps have been prepared. Moreover, if the maps were prepared from the photographs taken in winter when the glaciers are covered with snow, then it is not possible to map the lateral moraines accurately, which are also shown in the SOI maps. The use of topographical maps has also been mentioned in reports of the Geological Survey of India[13].

Thus, considering the potential of satellite images in mapping glaciers and the capability of GIS in carrying out spatial analysis, the present study is an attempt to map the glaciers in two adjacent basins of the Western Himalaya, with approximately the same altitude and latitudes and compare the changes in two time-frames with respect to three parameters, i.e. area, debris cover and area–altitude distribution on the glaciers. Area of the glaciers is considered here, as it is proportional to its volume[14]. Volume or size of the glaciers determines the time taken by them to respond to change in mass balance. For a given period different glaciers with different areas are expected to retreat or advance differently, provided there is an almost uniform change in the mass balance. The debris cover is another parameter considered to analyse the retreat, as many glaciers in the Himalaya are covered with moraines or rock debris. Debris hampers the incoming short wave (solar) and long wave (emitted from the earth's surface and re-emitted from the atmosphere) radiations from reaching the glaciers. The third parameter (area–altitude distribution of the glaciers) has been considered because retreat or advance of glaciers is the net result of long-term negative or positive mass balance respectively. Altitude has direct implications on the mass balance within a basin as the annul accumulation and ablation are also controlled by altitude. So, within the same climatic region, different glaciers may have contrasting responses to the same climatic signal[15]. On this basis the present study has been carried out on more than 350 glaciers (large valley glaciers to small glacierets).

The study area covers glaciers of the Warwan and Bhut sub-basins belonging to the Chenab Basin, Western Himalaya (Figure 1). The sub-basins are located in Jammu and Kashmir between 33°30′–34°21′N lat. and 75°39′–76°28′E long. and 33°15′–33°64′N lat. and 75°72′–76°78′E long. with an area of 4,828.4 sq. km and 2,285.4 sq. km respectively. In the Warwan Basin, the largest glacier covers 51.8 sq. km, (lat./long. 33°45′52.43″N/76°07′02.15″E) followed by one with an area of 48.7 sq. km (lat./long. 33°32′14.16″N/76°06′07.25″E). In case of the Bhut Basin, the largest glacier has an area of 49.9 sq. km (lat./long. 33°12′10.21″N/76°43′05.08″E). Most of the glaciers in the two sub-basins have slope in the range 10°–20°. Both the basins lie between altitude 1,100 and 6,500 m. Most of the larger-sized glaciers are covered by rock fragments in the ablation zones, whereas smaller glaciers are debris-free. Majority of the glaciers in the Bhut Basin are moraine-covered than those of the Warwan Basin. The host rocks for the glaciers to rest are gneisses and schist of the Central Crystalline Zone. One major difference between the glaciers of the two basins is that glaciers of the Bhut Basin are mainly south-facing whereas those of the Warwan Basin are north to north-west-facing (Figure 2).

The following data have been used in the study. (i) SOI topographical maps of 1962 at 1 : 50,000 scale, from which glacier extents have been adopted. (ii) IRS LISS III (Linear Imaging Self-Scanner) images of ablation season, 9 September 2001 and 10 August 2002 for extraction of glacier extent. LISS III images have four spectral bands: band 1 (0.52–0.59 μm), band 2 (0.62–0.68 μm), band 3 (0.77–0.86 μm) at 23.5 m resolution and band 4 (1.55–1.70 μm) at 56 m resolution. (iii) SRTM DEM (Shuttle Radar Topography Mission Digital Elevation Model) for estimation of area–altitude distribution of the glaciated region of each basin. These data provide a global coverage of the earth's DEM with 90 m spatial resolution and about 15 m vertical accuracy[16]. This source of DEM is commonly used for many thematic applications.

The following steps were executed to map the glacier extent and its change detection over a period of time.

Georeferencing: The IRS LISS III data (FCC of bands 1–4) covering the two basins were georeferenced with the corresponding SOI topographical maps. While executing georeferencing, it was made sure that the same datum and projection are used for the map and images. The datum and projection used in the present study are Everest and Geographic respectively. Georeferencing of the images was done by taking ground control points (GCPs) from the topographical maps. The GCPs included mainly the drainage intersections. The positional accuracy of the topographical map at 1 : 50,000 scale is given as 12.5 m, which can be considered for the GCPs too. In the present

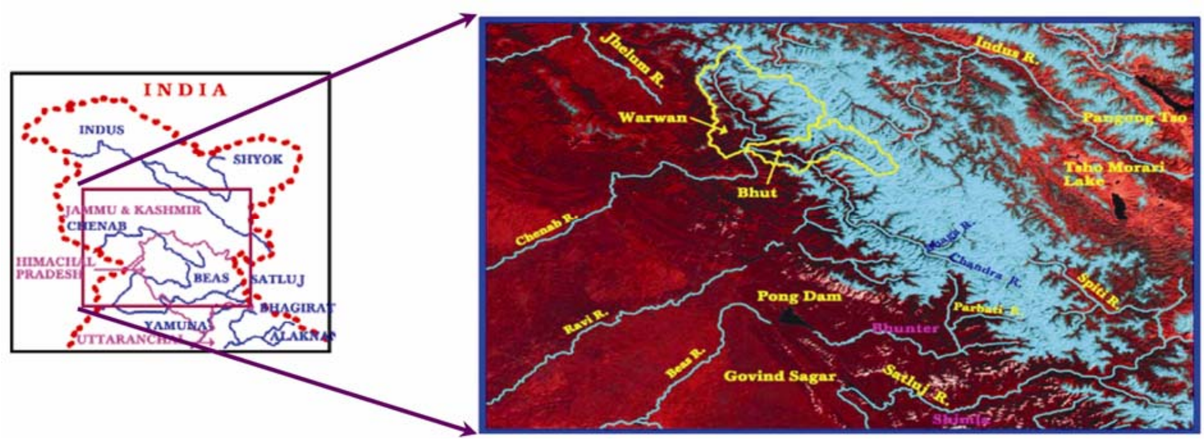

Figure 1. Location map of the study area.

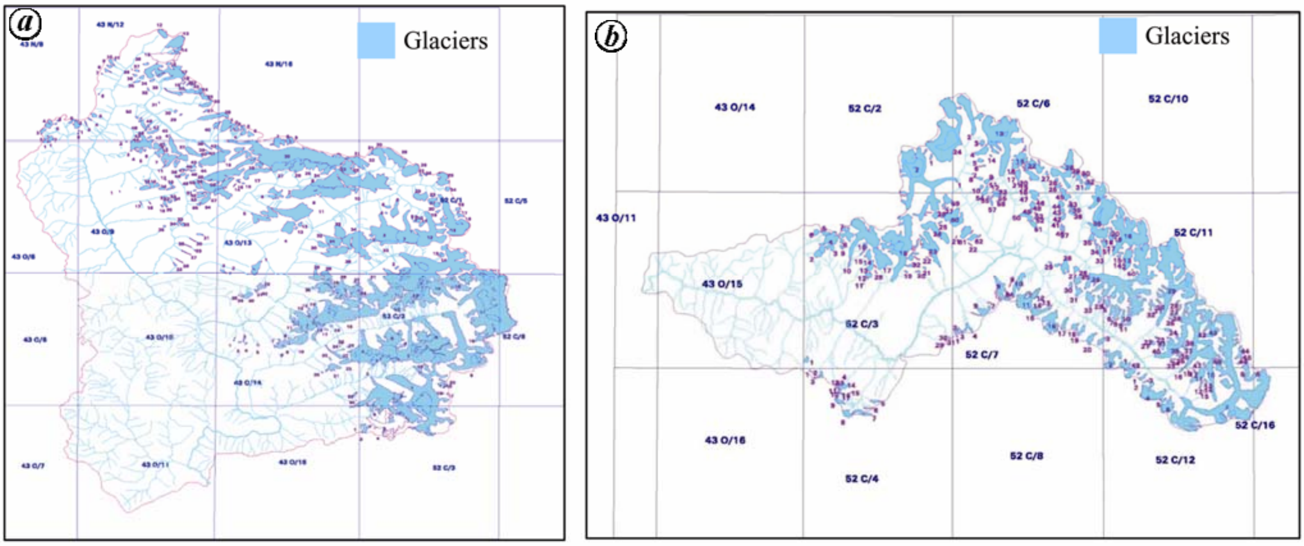

Figure 2. Glacier index map of (***a***) Warwan and (***b***) Bhut basins.

case, approximately 100 GCPs were used. Polynomial model was used for registration. The registration was performed at sub-pixel level. The images were resampled using nearest neighbour method. This provides coordinates for the images. The ERDAS imagine version 9.1 was used for the pre-processing of digital images.

Glacier mapping: Glacier extent was first adopted from topographical maps and then mapped from satellite images. Mapping from images requires use of elements of visual interpretation, such as unique reflectance of snow and ice, shape of the valley occupied by the glaciers, the flow lines of ice movement, rough texture of the debris on the ablation zone, and the shadow of the steep mountain peaks and presence of vegetated parts of the mountains. The SWIR band was used to discriminate cloud and snow as in many cases the glaciers are covered by clouds in ridges. The snout of a glacier is the most important feature for monitoring it, because the movement of the snout helps in recognizing the advance or retreat of the glaciers. Sometimes snouts of many glaciers were not distinct on the images due to debris cover. In such cases various other indicators such as location of origin of streams from the glaciers, presence of distinct geomorphic features in the form of braided streams, lakes, glacio–fluvio sands, etc. helped in the identification of snouts. Additionally, changes of slope or elevation near the snouts observed through DEM from SRTM, also helped in the identification of snouts.

For detection of change in area of the glaciers, only the change around the ablation zones was considered as the accumulation zone is dynamic in terms of snow cover and net change in the glacier is reflected at the snout. Enough care was taken to see that changes in the extent do not cross over the past lateral moraines.

Extraction of moraine cover: For delineation of moraine cover, an algorithm for computing Normalized Difference Snow Index (NDSI) was used within each glacier extent. The NDSI algorithm automatically extracts snow and ice from the images. It is computed as follows[17,18].

$$\mathrm{NDSI} = \frac{\text{Reflectance of green} - \text{Reflectance of SWIR}}{\text{Reflectance of green} + \text{Reflectance of SWIR}}.$$

The basic premise of this index is that snow is characterized by a high reflectance in the visible region and a strong absorption in the SWIR region. Therefore, NDSI can extract snow from non-snowy regions of the image. A threshold value of 0.4 is good enough for this distinction. The remaining part of the glacier is the moraine cover. The extracted moraine cover area thus delineated was also verified visually on the images.

Area–altitude distribution: Area–altitude distribution of the glaciers is required to understand the cover of ice at different altitude zones as the melting of ice is profoundly controlled by the altitude. For this purpose elevation contours at intervals of 300 m were derived from SRTM DEM. Glacier boundaries were overlaid on the elevation zones in a GIS environment and based on the intersection of two layers, the area of the glaciers was computed within each elevation zone.

Deglaciation was observed in both the Warwan and Bhut Basins during 1962–2001. However, the magnitude of deglaciation differed. In the Warwan Basin, 19% of the total glaciated area was vacated, whereas it was only 9% in the Bhut Basin (Table 1). This gives an annual loss of 0.49% and 0.23% respectively, for the Warwan and Bhut Basins. Another estimate of 0.4% per year from 1969 to 2010 has been given Schmidt and Nusser[3], for the Trans Himalayan glaciers, 0.2–0.7% for glaciers of the Indian catchments[19], 0.3% for glaciers of Bhutan and 0.3–0.6% for glaciers of Tibet[20]. These results are in contrast with the state of the glaciers in the Karakoram region, which are either advancing or stable[21,22].

The magnitude of the glacial retreat within each basin also differed. It varied from 0 (no change) to 100% (for the vanished glaciers). The loss in area of the glaciers is shown in Figures 3 *a*, 3 *b* and 4. There is no case of increase in the size of the glaciers. Many glaciers have also been found stable. This is explained in the following paragraphs.

Table 1. Salient features distinguishing retreat in the Warwan and Bhut basins

Parameter	Warwan Basin	Bhut Basin
Number of glaciers in 1962	230	140
Number of glaciers in 2001/02	250	145
Total glaciated area in 1962 (sq. km)	746	427.3
Total glaciated area in 2001/02 (sq. km)	604.3	388.8
Mean glacier area	3.2	3.05
Loss in area (%)	19 ± 5	9 ± 5
Mean glacier loss (sq. km)	0.6	0.3
Percentage of moraine cover	18	30

One of the reasons for the difference in the magnitude of deglaciation in the two basins could be the size of the glaciers. The smaller glaciers show a faster change in area than the large glaciers as the time taken by the glaciers to adjust to change in mass balance is inversely proportional to the size of the glaciers. In other words, adjustment of mass balance is faster in smaller glaciers than in large glaciers. For example, in the Warwan Basin, glaciers less than 1 sq. km show a loss of 36% in area, those between 1 and 3 sq. km show a loss of 32%, and those between 3 and 10 sq. km show a loss of 17%. Glaciers greater than 10 sq. km show deglaciation of 15%. Though glaciers greater than 10 sq. km are few in both the basins, they cover a large percentage of the total glaciated area. These glaciers are therefore significant for the analysis. The loss shown by these glaciers is higher in the Warwan Basin (15%) than that in the Bhut Basin (7%). Because the glaciers are larger in the Bhut Basin than in the Warwan Basin in each size class (Figure 5), this is reflected in terms of retreat. Size is not the cause for the difference, but it is the reason for reflection of difference in retreat on the surface.

The other factors which play a significant role in the variation of mass balance and thus retreat or advance of glaciers are altitude and latitude, as these control the temperature gradients on the earth's surface. In case of these two basins, latitudinal differences are negligible and thus can be ignored. The glaciers at high latitude or altitude require higher amount of energy to melt. The survival of glacier increases with altitude because mean temperature decreases with air density[23]. Due to this air at higher altitude is less efficient in holding heat energy than denser air at lower altitude[24]. Thus, when the glaciated region is at a higher altitude, it will require higher amount of energy to melt than glaciers at lower altitude within a given time-period. It has been observed that in the Warwan Basin 20% of the glaciers lie above 5,100 m altitude, whereas in the Bhut Basin it is 30% (Figure 6). Probably this is one of the reasons for higher loss in area of the Warwan Basin than that in the Bhut Basin. The variation in the distribution of the glaciated region in two different sub-basins based on altitude is shown in Figure 7.

Debris cover is one of the most important constituents of a glacier system as it can greatly influence the surface energy balance and process of glacier melting. Moraine cover is normally spread over on the ablation zones of valley glaciers. The ablation zones of the valley glaciers have gentle to very gentle slopes which restrict the faster movement of debris. Ice fields or ice caps normally lie on the steeper slopes and do not sustain the rock fragments on its surface. The presence of moraine on the ablation zones restricts the insulation thus hamper the melting rates of glaciers. It acts as thermal barrier between ice and the atmosphere, reducing the energy flux to the ice surface[23]. Though it has been argued that thin

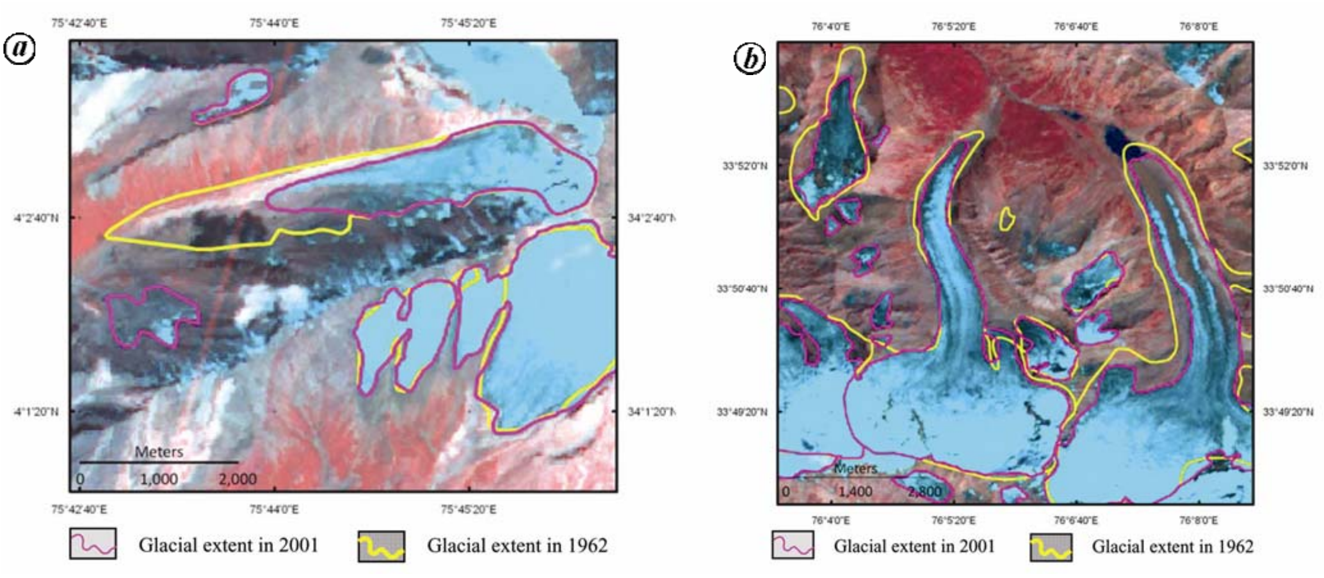

Figure 3. Glaciers located in the Warwan sub-basin showing loss in area, 1962–2001.

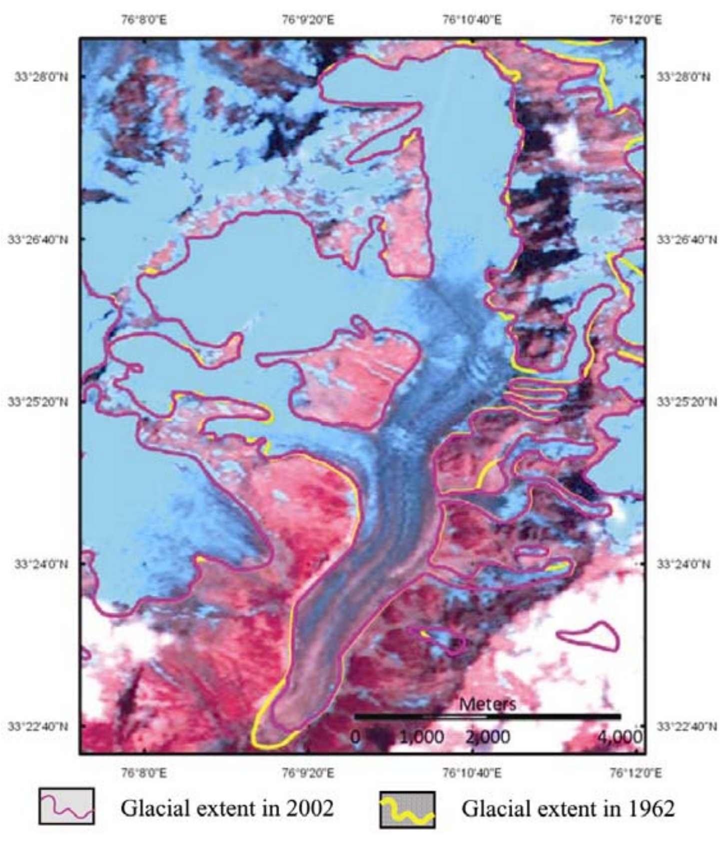

Figure 4. Glaciers located in the Bhut sub-basin showing loss in area, 1962–2002.

moraine helps in the conduction of heat and allows higher melting, the glaciers of the Bhut Basin have higher percentage of moraine. In case of the Warwan sub-basin, the moraine cover is only 18%, whereas it is 30% in the Bhut sub-basin (Table 1). Probably, this is the reason that glaciers in the Warwan Basin appear to have lost more area than those in the Bhut Basin.

As mentioned earlier, glaciers of the Bhut Basin are mainly south-facing and those in the Warwan Basin are north to northwest-facing. The aspect is also an important parameter in studies of glacier fluctuations. It is normally argued that south-facing glaciers retreat faster than north-facing glaciers. It is not only the aspect which controls the glacier extent, but the aforementioned factors collectively play a role in the advance or retreat of glaciers. Probably this is the reason that glaciers of the Bhut Basin show lesser retreat than those of the Warwan Basin.

Overall the glacier variations are the result of long-term variations only in mass balance, which is further controlled by climatic variations in terms of precipitation and melting due to net change in energy balance. Retreat or advance of glaciers is only the manifestation on the surface of the variation in mass balance.

There are two types of accuracies which are normally determined in producing maps from remote sensing data. The positional accuracy determines the difference in the coordinates for a point on the map and its actual location on the ground. The thematic accuracy is related to accuracy of interpretation. The two accuracies are discussed below.

The positional accuracy depends on the spatial resolution, datum, projection, scale of mapping and the number of GCPs used for registration of the images. If multi-temporal images are used, then the following formula is used for estimating uncertainty[25].

$$\text{Uncertainty} = \sqrt{a^2 + b^2} + \text{Regi},$$

where a is the pixel resolution of imagery 1, b the pixel resolution of imagery 2 and Regi is the registration error.

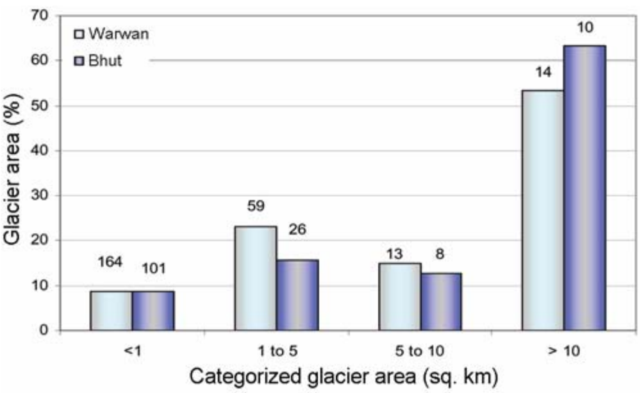

Figure 5. Number of glaciers of the Warwan and Bhut Basins in specific classes of areal extent.

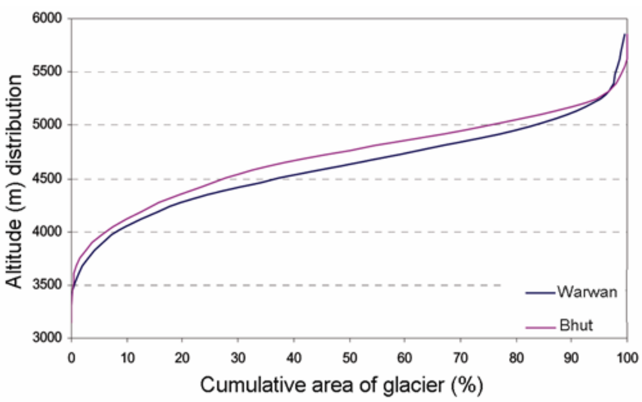

Figure 6. Area–altitude distribution of glaciers in the Warwan and Bhut basins.

The above formula has been modified here for registration of topographical maps and the image. The positional accuracy of topographical maps is normally taken as 12.5 m at 1 : 50,000 scale. This has been used equivalent to spatial resolution of an image. The pixel resolution of LISS III images is 23.5 m. Using the above formula the positional error of mapping has been computed as follows.

$$\text{Uncertainty} = \sqrt{12.5^2 + 23.5^2} + 12.5 = 39.1\ \text{m}.$$

Thematic accuracy depends on manual delineation in case of visual interpretation or the algorithms used in case of digital classification. The present work is based on visual interpretation of the images. A standard method of estimating accuracy while using digital classification is by generating a confusion matrix of mapped classes[26]. This method is suitable for multiple thematic classes. In the present study only two classes, i.e. glacier and non-glacier areas have been mapped using elements of visual interpretation. In such cases the uncertainty in the

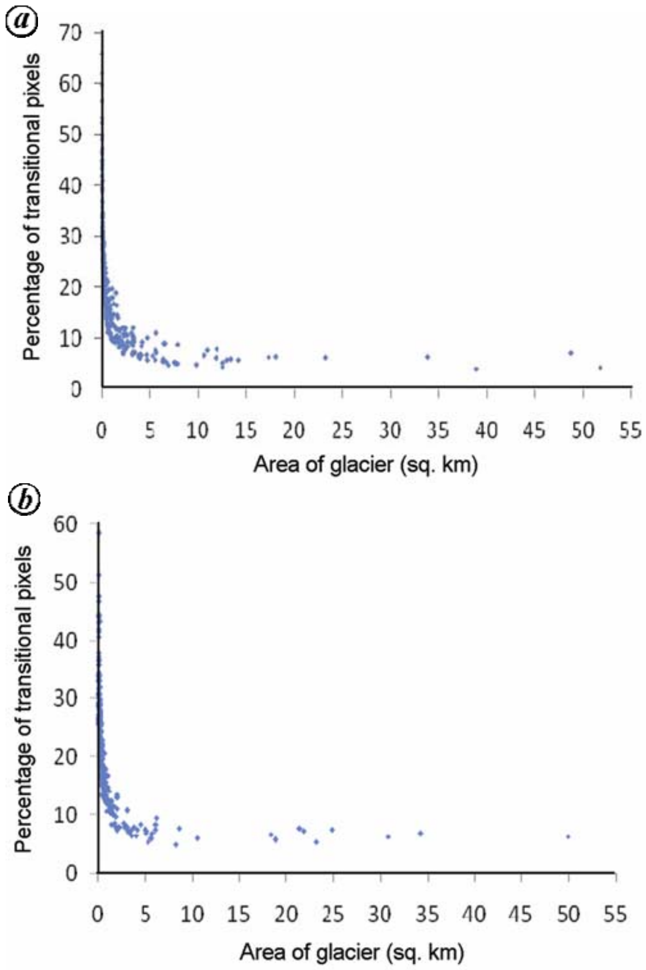

Figure 7. Uncertainty in mapping of glaciers in the (***a***) Warwan and (***b***) Bhut basins.

mapping normally occurs at the boundary of the two classes. Using this as the basis, the following approach has been used to estimate the uncertainty in area of mapping.

$$\text{Uncertainty in glacial area (\%)} = \frac{\text{Number of pixels on the periphery}}{\text{Total pixels of a glacier}} \times 100.$$

A plot has been generated between area of a glacier polygon and the number of pixels at the boundary of the glacier and non-glaciated regions (Figure 7). This plot shows high percentage of uncertainty for a few glaciers. But for majority of the small glaciers (less than 2.5 sq. km) the uncertainty is found to be within 20%. For glaciers smaller than 2.5 sq. km (uncertainty up to 20%), the percentage of loss in the Warwan and Bhut Basins is 33 and 3 respectively. The retreat of the glaciers less than 2.5 sq. km, is subjected to more inaccuracy, glaciers larger than 2.5 sq. km. For glaciers larger than 2.5 sq. km, the uncertainty almost stabilizes at 5% or lesser. It has been observed that loss in area of glaciers greater than 2.5 sq. km for the Warwan and Bhut Basins is 16% and 8% respectively. At the basin level, the loss in area for the Warwan and Bhut Basins is 141.7 sq. km and 38.5 sq. km respectively, which corresponds to an uncertainty of approximately 5% or lesser.

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