USE OF LANDSAT IMAGERY FOR MAPPING DEBRIS-COVERED GLACIERS IN THE KARAKORAM HIMALAYAS, NORTHERN PAKISTAN

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ABSTRACT - Debris-covered glaciers, unlike other types of glaciers, are difficult to map using visible and infrared imagery. Supraglacial debris cover, snow cover and debris-covered glaciers were mapped using Landsat images acquired from October in 1998 to October 2002 and a digital elevation model (DEM) which was derived from Shuttle Radar Topographic Mission (SRTM) acquired in 2002. Image processing and mapping were done using ERDAS Imagine and ESRI ArcGIS software packages. Supraglacial debris and snow cover were mapped efficiently using various methods. The results of these methods were found to give comparable results. However some discrepancies may arise due to the poor spatial resolution of images, seasonal variations and lack of fieldwork. Debris-covered glaciers were also mapped by using different methods. Firstly using thermal imagery of Landsat and the second method was derived from the results of debris cover maps and NDVI images. Changes in debris extent and debris-covered glaciers in the study site during this period were also calculated. It is expected that a high spatial and spectral resolution imagery combined with field work would produce better map of debris-covered glaciers.

1 INTRODUCTION

Glaciers consist principally of ice crystals as the principal component with air, water and rock debris. Glacier ice is derived indirectly from the precipitation of snow or ice crystals from the atmosphere, or directly from liquid transformed to ice at the glacier surface (SUGDEN and JOHN, 1976). Glacier systems help in driving climate change by undergoing modifications and interactions with the atmosphere (BENNETT and GLASSER, 1996). About 30% of the Earth’s land surface has been covered by glaciers; 10% of the land is permanently ice-covered at present, and 10% is permanently frozen; about 50% of the land is covered by snow and ice in the northern-hemisphere winter and more than 75% of the World’s fresh water is contained in glaciers, which provide irrigation water for some of the most densely populated areas of the World (KNIGHT, 1999). Hence an understanding of glaciers is necessity in understanding the Earth’s surface.

The surface of glaciers can be either clean or debris-covered. The source of debris on the glaciers may vary from place to place. Mainly the activities which cause debris cover on glaciers are a) mass movements from adjacent mountain slopes b) wind-blown dust c) volcanic eruptions d) salts and micro organisms from sea spray e) meteorites and f) pollutants (Benn and Evans, 1998). In glacial environments, frost action is the principal mechanism in the release of debris from rock slopes, acting at the granular scale (microgelevation) or exploiting bedding planes or joints (macrogelevation) (Benn and Evans, 1998). The two main processes are firstly that water undergoes 9% expansion of volume upon freezing, which can force apart the sides of a water filled pore or crack causing crack extension and secondly by the capillary pressure, liquid water may enter into the freezing centres to nourish expanding lenses of segregation ice, which progressively cause the separation of the rock. This mainly happens at a temperature range of -4 to -15 °C (BENN and EVANS, 1998). Snow and ice avalanching is also an important mechanism for transporting debris on to the glacier surfaces, especially in high mountain environments such as the Himalayas, where large quantities of snow can accumulate on unstable slopes during snowfall. (BENN and EVANS, 1998; RAINA and SRIVASTAVA, 2008). When these snow slopes collapse, it will result in large and destructive avalanches, which would be enough to detach debris from underlying rock surfaces (BENN and EVANS, 1998).

In recent decades our understanding of glacier fluctuations in the past has greatly improved due to the understanding of modern climate-glacier relationships as well as due to the rapid development of technologies and concepts in paleoclimatology (SOLOMINA et al., 2008). Global warming scenarios have tended to invoke images of rising global sea level, increased melting of World’s ice bodies, and accelerated calving rates at the marine margins. But a warmer World is not necessarily a non-glacierized world (BENN and EVANS, 1998). Debris covered glaciers, in spite of the global warming, are found to be expanding in some parts of the Karakoram region of the Himalayas (BELO et al., 2008; MAYER et al., 2006). The changes of glaciers in debris-covered and debris-free areas may affect local climate (TAKEUCHI et al., 2000). Some scientists predict that the total volume of present glaciers will be halved by 2050 and only a few glaciers, such as in the mountains of inner Alaska, Arctic Archipelagos, in Karakoram mountains of the Himalayas and in the Northern Himalaya, will survive global warming (HASNAIN, 1999). Hence a detailed knowledge of debris covered glaciers is important in climate studies, especially in understanding the complex interrelation between climate change and glacier expansion and ablation.

Not many studies have been conducted on the debris covered glaciers in the Himalayas. The study on the recent evolution of Liligo glacier in Karakoram, Pakistan (Mayer et al., 2006; Belo et al., 2008) added some light to this area. Using a series of satellite images from 1973-2001, such as Landsat series and ASTER, Liligo glacier is described as an example of rapidly advancing Karakoram debris-covered glacier. Field work and remote sensing data clearly show that this glacier experienced an advance of about 2.1 km during the past three decades, at a mean advance of 60m per year (BELO et al., 2008). Debris covered glaciers show an altered sensitivity towards climate change compared with that of debris free glaciers. Due to the reduction in the ablation rate beneath the debris cover, such glaciers tend to advance very rapidly. Large rocks falling on the glaciers can initiate advances (KIRKBRIDE, 2002). Debris cover also promotes the resedimentation process in dead-ice environments due to the melting of ice underneath (SCHOMACKER, 2008). The effect of the debris layer is not well understood. At present, the knowledge of glacial hydrology is lagging behind the theoretical studies, but in the last decades, the science of glacial hydrology has become integrated into the physics of ice masses (MENZIES, 1995).

2 STUDY SITE AND DATA

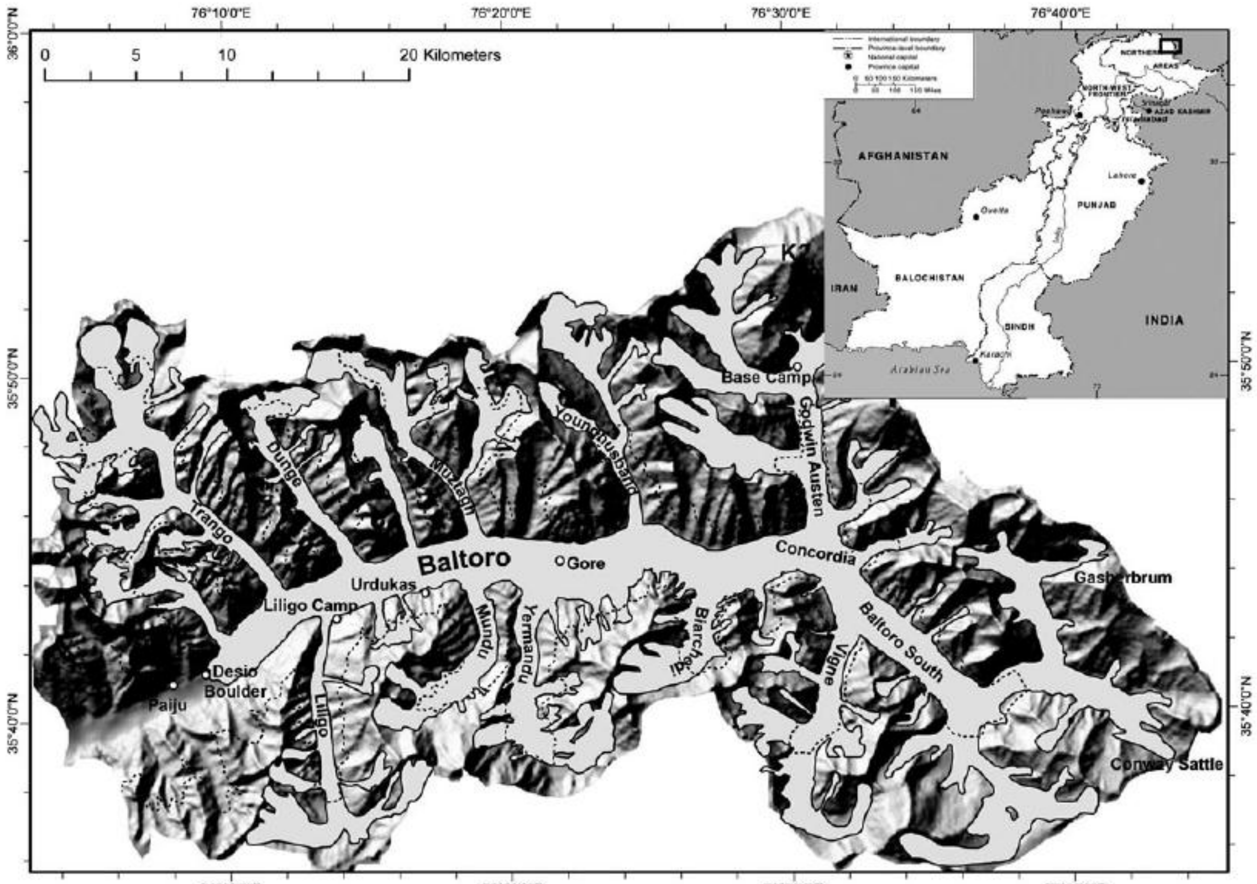

Figure 1 - Overview of the Baltoro drainage basin and the location of Baltoro glacier in Pakistan (MAYER et al., 2006).

Baltoro glacier (35° 35′ – 35° 56′ N, 76° 04′ – 76° 46′ E) is one of the spectacular debris-covered glaciers in the Karakoran Himalayas in Northern Pakistan, with an area of 1500 square km and a length of 64 km. It is one of the longest glaciers outside the polar region. The main glacier tongue forms below Concordia at a height of 4600 m above the sea level, with debris cover oriented towards the east-west direction. An overview of the Baltoro glacier is given in figure 1.

The images used for this study were derived from Landsat series and Digital Elevation Models (DEMs) from shuttle radar topographic mission (SRTM). Landsat images available were previously orthorectified and hence no geometric correction is required during the pre-processing of the images. Two Landsat images were used which were acquired in October 1998 and October 2002. These images were found to be cloud free and both were acquired during the same season. Another image acquired in March 2001 is also processed for a sequential continuity in the study. The Shuttle Radar Topographic Machine (SRTM) images are freely available from the USGS website. The space shuttle Endeavour was used to carry SRTM (EHSANI and QUIEL, 2009). These images provide a map of the global landmass areas produced using two simultaneous radar systems operating in X and C bands. Synthetic Aperture Radar (SAR) interferometry is used in SRTM to produce a consistent DEM, covering all landmass on the Earth between 60° N and 57° S (EHSANI and QUIEL, 2009). The SRTM images are suitable for obtaining digital elevation data on a somewhat global scale to generate a complete high resolution digital topographic database of the Earth (EHSANI and QUIEL, 2009). The downloaded SRTM images have been previously georeferenced to latitude and longitude. Due to the difference in projection system, the SRTM data were reprojected into Universal Transverse Mercator UTM zone 34 using ArcGIS and ERDAS Imagine tools. The spatial resolution of the downloaded SRTM data is 90 meters (Ehsani and Quiel, 2009) with a ± 15 m vertical accuracy (KAUR et al., 2009).

3 METHODOLOGY AND RESULTS

Preprocessing steps such as creating subsets and cosmetic operations were done before the detailed processing of images. The entire research has been divided into three sub-sections. First step was the mapping of the extent of supraglacial debris cover. Secondly mapping of snow cover was done in the study area. Finally debris-covered glaciers in the Baltoro glacier system were mapped.

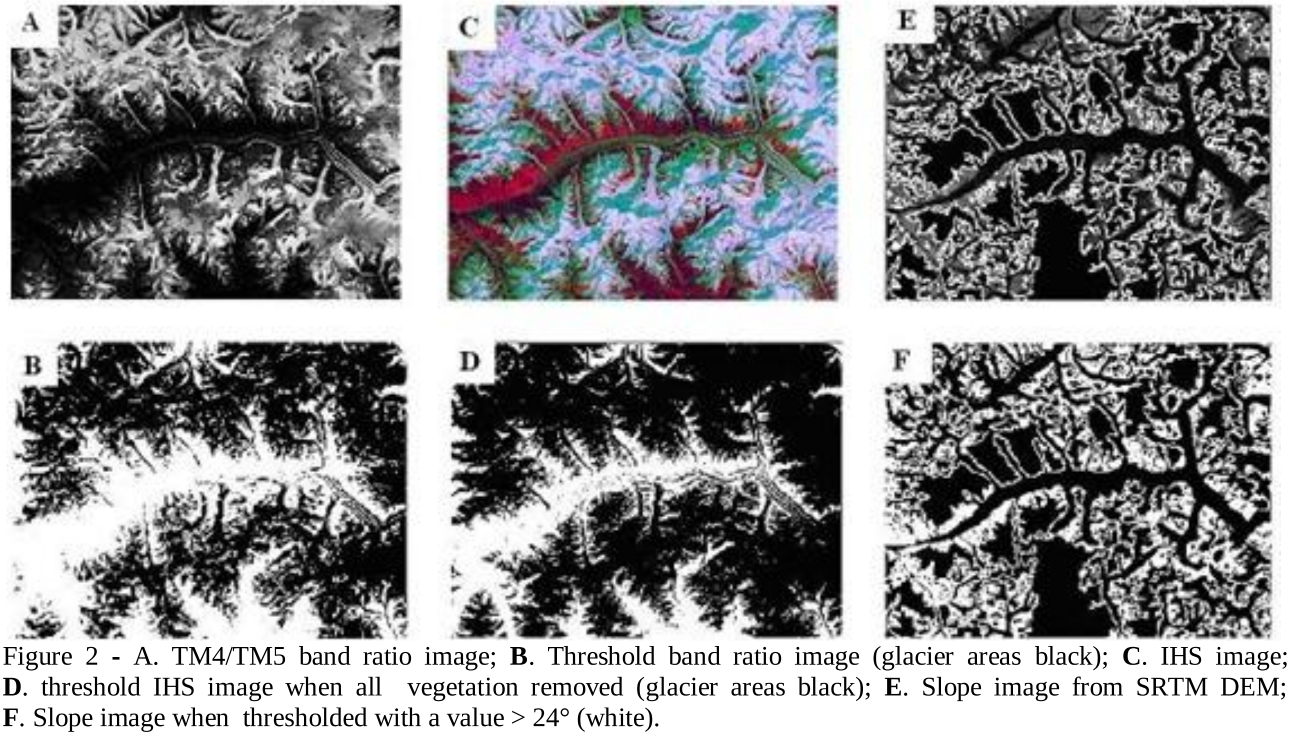

Figure 2 - A. TM4/TM5 band ratio image; **B**. Threshold band ratio image (glacier areas black); **C**. IHS image; **D**. threshold IHS image when all vegetation removed (glacier areas black); **E**. Slope image from SRTM DEM; **F**. Slope image when thresholded with a value > 24° (white).

3.1 Mapping of Supraglacial debris cover

Supraglacial debris cover was mapped using three methods. Paul et al. (2004) method is followed in the first method. Here, the TM4/TM5 ratio image is segmented with a threshold value of 2.0 to separate ‘glacier’ from ‘other’ surface features. At the same time, the hue component of the IHS image derived TM 3,4 and 5 is segmented with a threshold value of 126 to separate vegetation from vegetation-free areas. Angle of slope is calculated from the SRTM DEM. It is assumed that debris will not remain stable on slopes greater than 24° (PAUL et al., 2004). All slope values greater than 24° were assigned a value of 0 (black) to produce the slope facet map.

All the above threshold images obtained were overlain and a classification of 'Glacier' (black) and 'other' (white) was obtained (figure 3A). The change in the debris cover from 1998 to 2002 is also calculated. In the second method, threshold images were produced in the same way as in the previous method. Instead of overlaying all threshold images, here, all the three images were arithmetically added. In the output image (Figure 3B), debris-free glacier was represented in black color as in the first method but a detailed classification of different debris types was obtained. When the output images were compared with the original images by visual inspection, it supported the validity of this method. Dark grey color represented the debris on the glacier margin and light grey represented debris, which is not in contact with glacier margin. The chance of finding glaciers beneath the second class of debris (light grey) is high. The white color represents the soil/rocks on mountain slopes greater than 24°, where debris cannot stand due to gravitational force, and is not of interest in this study. Here also the change in the debris cover from 1998 to 2002 is calculated. In the third method, the threshold images were produced from the TM4/TM5 band ratio image and IHS image by using the same method discussed in the first method. The area where the slope is >24° is not in study interest because it is assumed that the debris cannot stand if the slope is above this threshold value (PAUL et al., 2004). All such places were masked and a binary image is produced. In this image, black color represents places where slope is > 24° and white color represents where slope <24° (instead of that produced in method 1 and 2). The chance of finding the debris is higher in latter area. In the next step, the threshold band ratio image and the threshold IHS image were multiplied with the threshold slope image. Now these two resultant images were overlain (figure 3C). Here the white color represented the area of research interest i.e., the supraglacial debris cover (including a part of the non-supraglacial debris too).

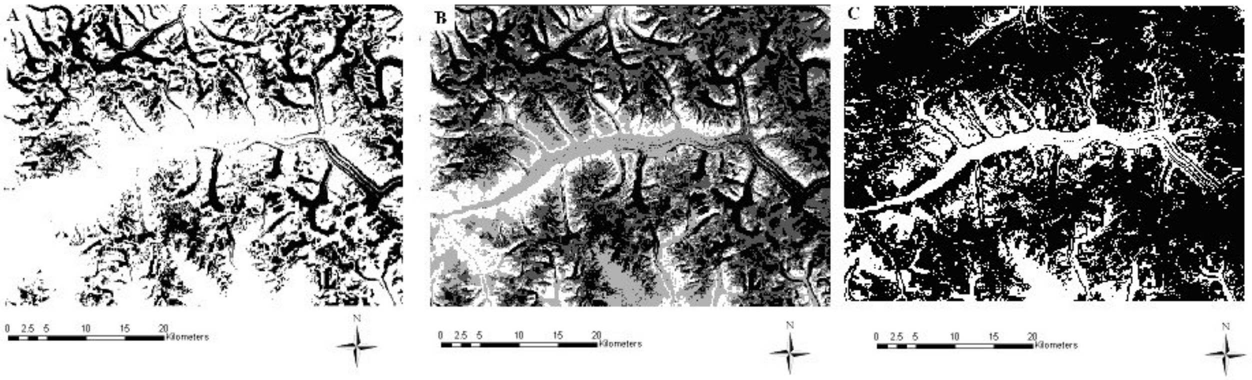

Figure 3 - Supraglacial debris cover maps using three methods

3.2 Snow cover mapping

The snow cover in the study site is mapped using three different methods. In the first method, the image is into either 'snow' or 'other' (figure 4A). The high reflection rate of snow in the visible waveband and high absorption in the near infrared waveband makes a high contrast between snow (white) and other surface features (WANG and LI, 2003). The original image was visually inspected and a number of spectrally similar classes were found using 15-20 training areas. The second method using digital numbers(DNs) based on the reflective properties of snow and other surface characteristics was proposed by WANG and LI (2003). Other factors such as time of the day, snow type, topography and atmospheric transmission were found to affect the selection of the threshold DN value for snow. Threshold values may also vary from image to image (Wang and Li, 2003). It is found that threshold values of 122.5 and 64.4 are suitable for mapping snow cover when applied to the Landsat TM2 waveband (figure 4B). The final method is done by using the Normalized Difference Snow Index (NDSI) derived from two TM bands, usually TM2 and TM5. The calculated NDSI can be used to discriminate snow, rock, and cloud cover (SILVERIO and JAQUET, 2005). After calculating the NDSI image, threshold values of 0.40 and 0.57 were applied and the suitability of these threshold values was done by the visual inspection of the output image (figure 4C) and it is found that there was more snow in 1998 compared to 2002.

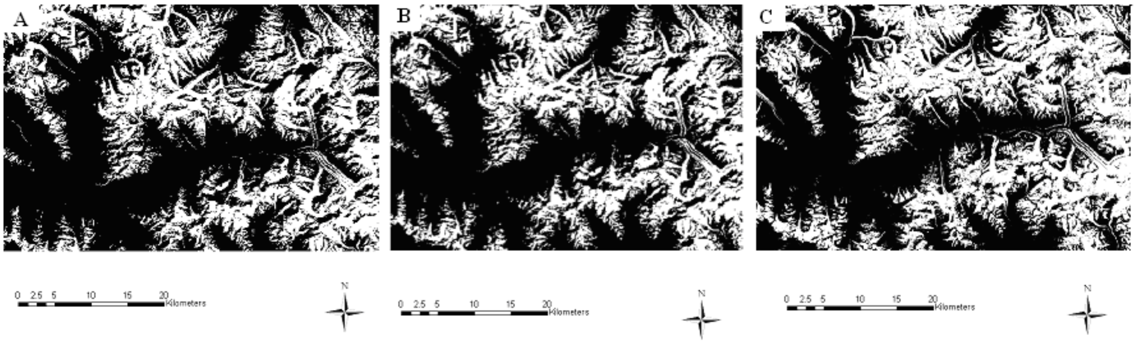

Figure 4 - Snow cover maps

3.3 Debris-covered glacier mapping

Debris-covered glaciers were mapped using two methods. In the first method, thermal waveband is used and in the second one, debris cover maps and NDVI images were used. The outputs of both the methods were compared. In first method, DNs corresponding to thermal response of Landsat (band TM6) were studied. It was found that threshold values between 105 and 115 of TM6 maps the debris covered glaciers more accurately.

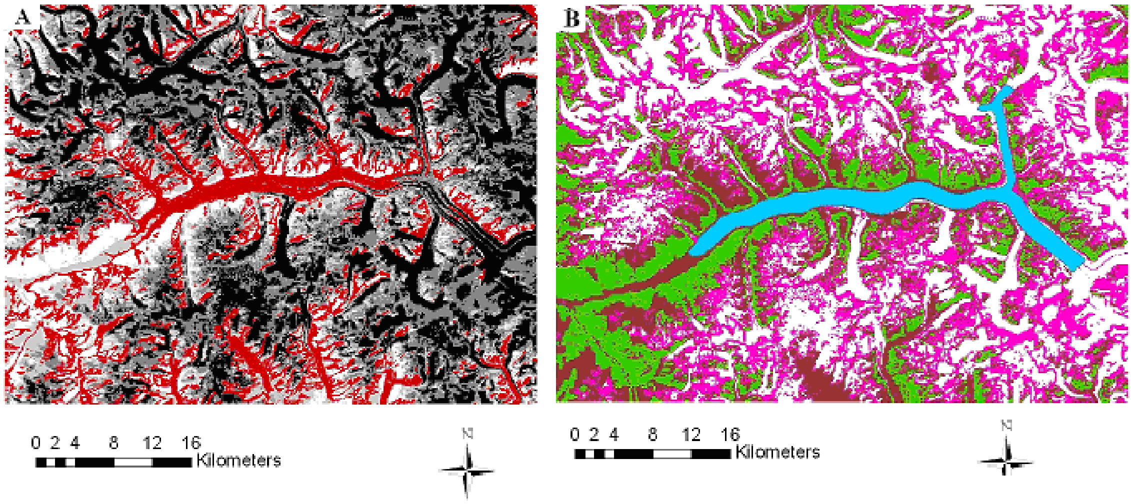

Figure 5 - Debris-covered glacier maps

The output image is converted to a shapefile and is viewed as shown in figure 5A. These shapefiles were compared with the South Asia glacier inventory to check the accuracy of the method and the similarity of the output image with the South Asia glacier inventory. In the second method (figure 5B), the origin of the Shigar River is taken as the snout position and the debris cover map calculated previously is taken as the area, where the possibility of finding debris-covered glacier is high. To estimate the origin of the Shigar River, NDVI image was calculated for both Landsat TM images in 1998 and 2002. A shapefile was created manually and the debris-covered glacier is visually inspected and compared with the debris cover maps obtained previously and with the South Asia glacier inventory.

4 CONCLUSIONS

Mapping of supraglacial debris cover in this study showed both advantages and disadvantages. The first and third methods were found to give only two classes - either debris or glacier and failed to differentiate various debris types. The output of the first method could not distinguish debris on high angled slopes and that on the low angles slopes, though a threshold was applied. The third method identified the debris cover above the glacier system and could distinguish the debris on the high angles slopes. The second method (arithmetic addition of the threshold images) was found to be a better method to map supraglacial debris cover and could give a detailed classification of topographic features. It is also found that more debris is accumulated at the origin of the Baltoro glacier system from 1998 to 2002. Rock avalanches might be accounted for such an increase in supraglacial debris cover (HEWITT, 1999). It is known that an increase in debris thickness beyond certain threshold value (2-4 cm) causes expansion of glaciers underneath them above certain thickness (BENN and EVANS, 1998; NAKAWO and RANA, 1999; KAYASTHA et al., 2000; HAMBREY and ALEAN, 2004).

The first method to map snow cover, which is a supervised classification technique, is found to be time consuming and the dependency on the expertise of the researcher in dealing with low spatial resolution images. The chance of missing snow pixels could be higher due to the presence of thin dust particles, pollen grains or other particulate matter over snow. Though the difference in reflective properties between snow and other features can be distinguished, during ablation season, the snow cover would be distributed in patches surrounded by snow-free areas and hence a single pixel may represent multiple surface features (WINTHER and HALL, 1999). The DN method used to map snow cover proved the suitability of a threshold value of 122.5 to map snow cover. The segmentation of NDSI images proved to be suitable in mapping snow cover, even though the threshold value could vary from place to place and even time to time (SILVERIO and JAQUET, 2005). It is seen that a segmentation of 0.57 (Wang and Li, 2003) gives a better snow map compared to that of 0.40 (SILVERIO and JAQUET, 2005). Even patches of snow were mapped by this method. The selection of the threshold value to create snow cover map is a critical task and a small change may lead to underestimation or overestimation of the areal extent of snow cover (GUPTA et al., 2005). The advantages of NDSI method include discrimination between snow and cloud and snow cover mapping under mountain shadows (GUPTA et al., 2005).

In first method to map the debris covered glaciers, a threshold value is applied to the thermal waveband (TM6) and this map was viewed as an ArcGIS shapefile to distinguish debris-covered glacier area from other topographic features. At the origin of the Baltoro glacier more accumulation of debris-covered glacier was found in 2002. It can be argued that the increased debris accumulation enhanced the expansion of glaciers underneath. However, it is found by visual inspection of the snow cover maps that there was more snow cover at the origin of the Baltoro glacier in 1998. The presence of snow cover may reduce the accuracy of the thermal imagery. If the ice-cored debris is covered by snow, this method would not work properly because the thermal radiation can be similar to that of debris-free glacier/snow/ice. The second method gave a comparable result with previous works (MIHALCEA et al., 2008; BELO et al., 2008). NDVI images have shown small change in the origin of Shigar River. The origin of the Shigar River has taken as the snout position and it was found by visual inspection that the snout position is moved back from 1998 to 2002 which shows that the Baltoro glacier has undergone ablation during this period, though it could be a seasonal phenomenon. The area of debris-covered glacier calculated using ArcGIS has shown that there is an overall increase in the glacier area.

In a nutshell, even though a number of limitations were there, this project can be used as an introductive study before active fieldwork on debris-covered glaciers. Since the spatial resolution of Landsat imagery is low (30 m), mixed pixels may arise in snow cover maps and debris cover maps. This limitation can be improved by using remotely sensed images of higher spatial resolution in future researches. Use of remotely sensed imagery having higher temporal resolution is also expected to be effective in monitoring gradual changes. There may be a chance of glacier expansion under the increased supraglacial debris cover in 2002 compared to 1998. But the presence of more snow in 1998 caused some difficulty in interpreting the imagery. A number of other discrepancies may also arise. First of all, the surface temperature of debris-covered glaciers depends on debris thickness (NAKAWO and RANA, 1999). During this study, the debris thickness is counted neither from field work data nor from remotely sensed imagery. Future research along with field work to estimate the debris thickness and surface temperature measurements could be able to uncover the expansion/ablation characteristics of debris-covered glaciers. Secondly, validity of the threshold values used to segment the debris-covered glacier can be questioned and these values can be improved to some finer values using direct data collection combined with remote sensing techniques. The hydrological records from the gauging stations near Shigar River basin would be helpful in making a conclusion on the expansion of debris-covered glaciers in the study site. Another valuable data is the precipitation rate because the differences in rainfall and snowfall quantities due to seasonal variations may affect the water availability in the gauging stations. These data should be considered before making a conclusion.

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