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A Remote sensing approach for monitoring debris-covered glaciers in the high altitude Karakoram Himalayas

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ABSTRACT

Debris-covered glaciers, unlike other types of glaciers, are difficult to map using visible and infrared imagery. Moreover, high altitude glaciers are difficult to map using fieldwork data due to the inaccessibility. In this study, supraglacial debris cover is mapped using Landsat TM and ETM+ images acquired from 1990 to 2010 and a digital elevation model (DEM) which is derived from Shuttle Radar Topographic Mission (SRTM) acquired in 2002. Image processing steps and vectorisation were done using Erdas 2011 and ArcGIS software packages. Different methods include manual, semi-automatic, modified semi-automatic, and automatic method using thermal wavebands. Application of band ratio images is also used. Changes in debris extent and debris-covered glaciers in the study site during this period were also calculated. These methods for mapping supraglacial debris cover 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. It is expected that a high spatial and spectral resolution imagery combined with field work data and surface ablation characteristics would produce better map of debris-covered glaciers.

Keywords: Debris-covered glaciers, Himalayas, NDSI, Landsat, SRTM

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 (Bennet 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 centers 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 re-sedimentation 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 sets

Baltoro glacier (35° 35′ – 35° 56′ N, 76° 04′ – 76° 46′ E) is one of the spectacular debris-covered glaciers in the Karakoran Himalayas, 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.

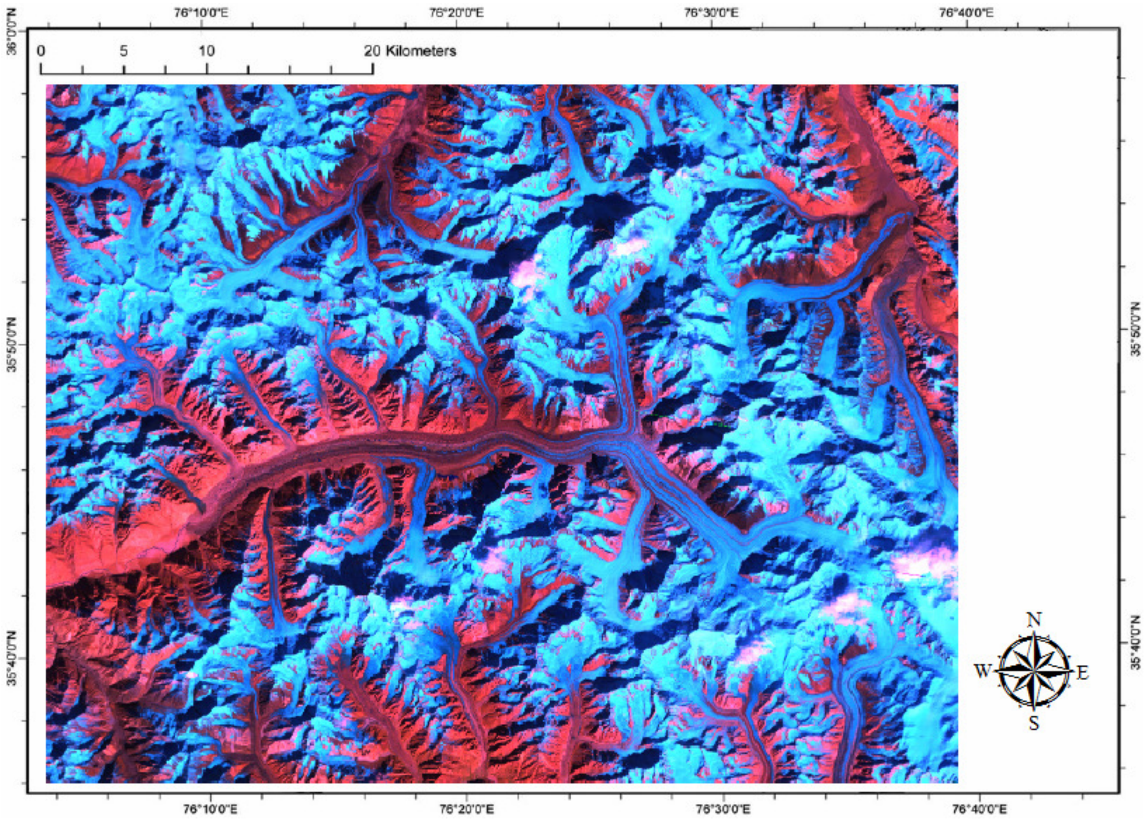

Figure 1: Overview of the debris-covered Baltoro glacier system in the Karakoram Himalayas (Derived from Landsat image).

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. Four Landsat images were used which were acquired in June 1990, October 1998, October 2002 and October 2010. 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 Methods and Results

Preprocessing steps such as creating subsets and cosmetic operations were done before the detailed processing of images. Supraglacial debris cover was mapped using manual, semi-automatic and automatic methods.

3.1 Manual approach

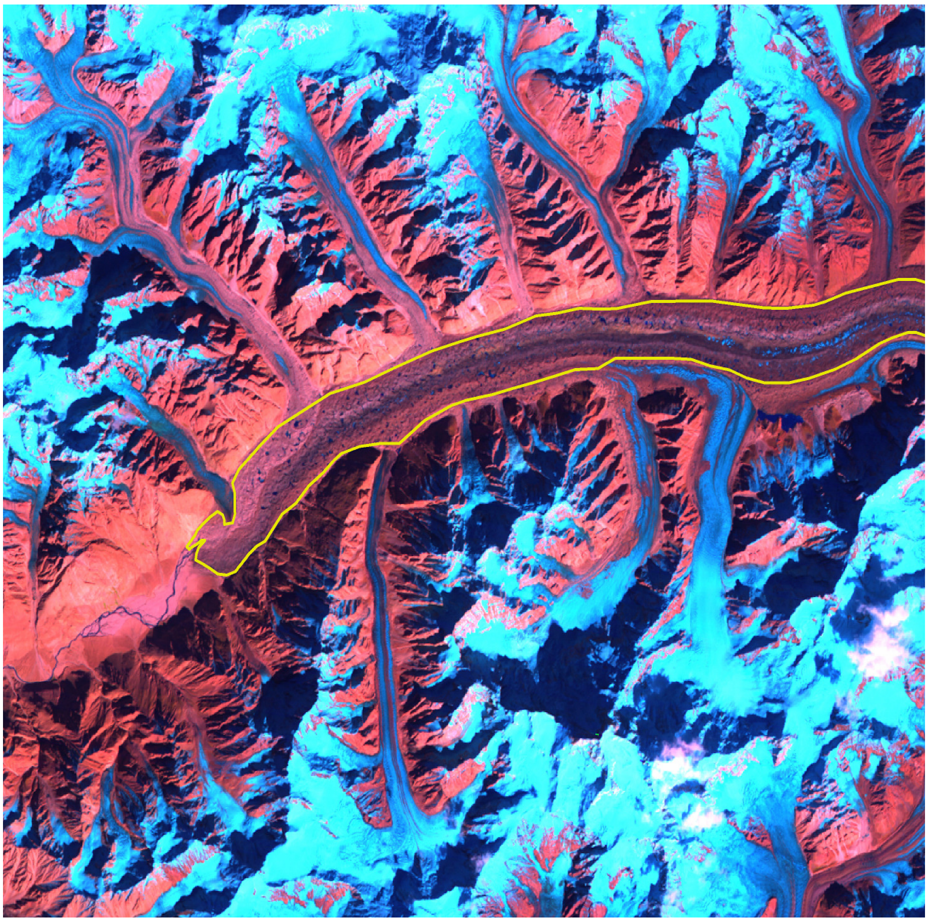

Figure 2: Manual delineation of debris-covered glacier.

The first approach is the manual delineation of debris-covered glaciers. (Figure 2). Here the origin of the Shighar River is taken as the snout position in each of the input images and the rest of the glacier is mapped by the visual inspection of the image. This method is found to be good in monitoring the snout position, even though it is time consuming and the accuracy is depending on the expertise of the user.

3.2 Semi-automatic methods

Paul et al. (2004) method is followed in this 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.

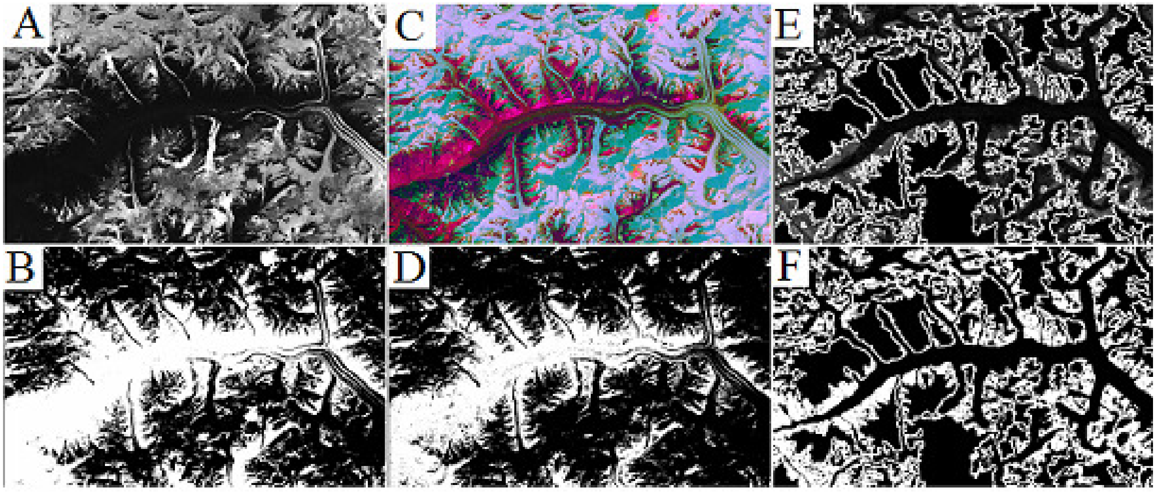

Figure 3: A. TM4/TM5 band ratio image; **B**. Threshold band ratio image (glacier areas black); **C**. IHS image; **D**. threshold IHS image when all vegetation removed (glacier areas black); **E**. Slope image from SRTM DEM; **F**. Slope image when thresholded with a value > 24° (white).

All the above threshold images obtained were overlain and in the output image (Figure 4A), debris-free glacier was represented in black color and 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 supraglacial debris. 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. The change in the debris cover from 1990 to 2010 is calculated.

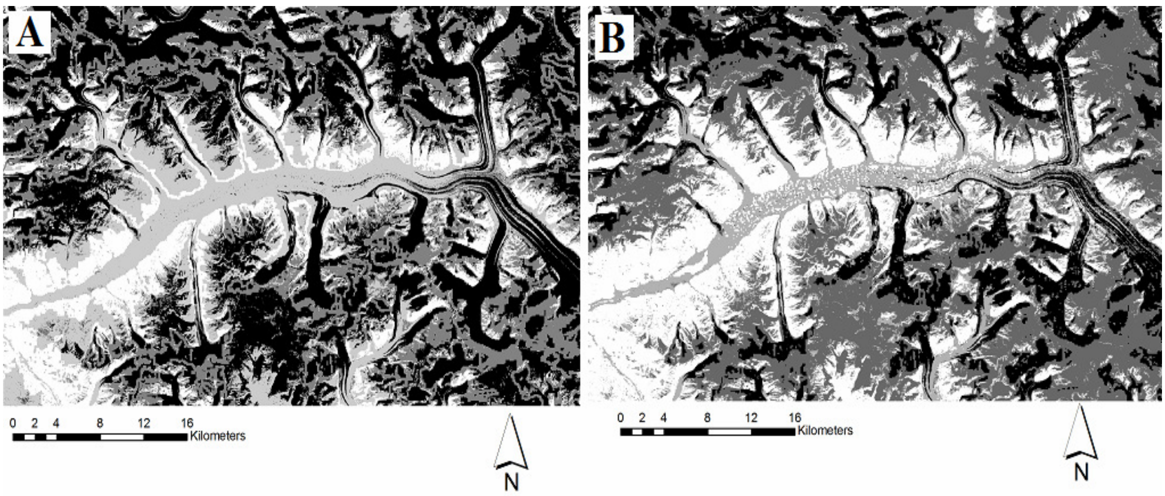

Figure 4: Supraglacial debris cover maps (light grey): A. semi-automatic method; B. modified semi-automatic approach

During this research, an algorithm similar to the one given above with two threshold values is introduced, in order to fit the slope values in the Himalayan region. The upper threshold slope value of 24^o is maintained the same but a lower threshold value of 0^o is also applied (figure 4B). By doing this, supraglacial glacial lakes and rivers having a slope of zero can be eliminated so as to get the snout position (note that the origin of the Shighar River is taken as the snout position). When compared to manual and other automatic methods, this algorithm is found to give comparable results.

3.3 Automatic debris-covered glacier maps using thermal imagery

Debris-covered glaciers were mapped by an automated algorithm using thermal waveband. The outputs is compared with the above methods. In this method, DNs corresponding to thermal response of Landsat (band TM6) were studied. It is found that threshold values between 105 and 115 of TM6 could segment debris covered glaciers accurately (figure 5). The output raster can be converted to a shapefile in order to calculate the surface parameters such as surface area and length, and is viewed as shown in figure 5. 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.

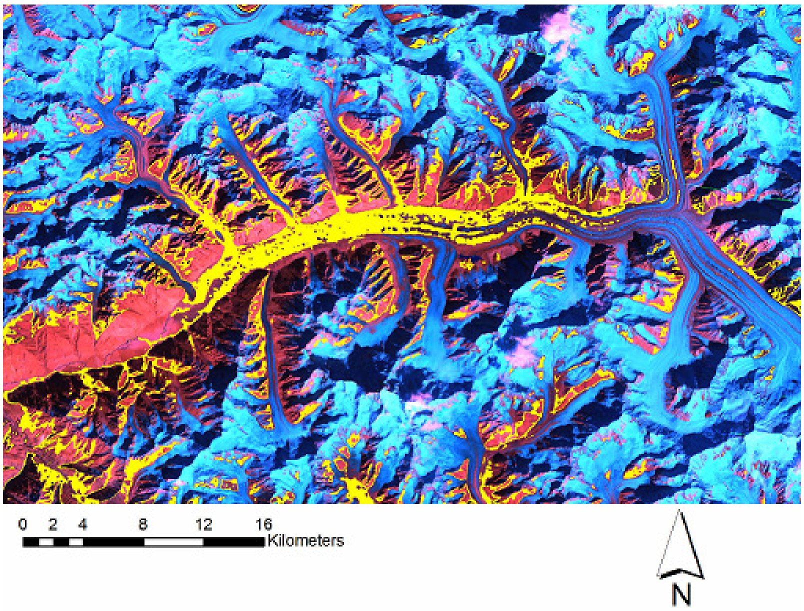

Figure 5: Automatic debris-covered glacier (yellow) mapping using thermal imagery

4. Discussion and conclusions

Mapping of supraglacial debris cover in this study has shown both advantages and disadvantages. The manual approach is found to give an accurate map but time consumption is very high. The accuracy depends highly on the researcher's skill and the spectral similarity of various surrounding objects makes difficulty in decision making. When combined with other automatic algorithms, this method could be improved. Semi-automatic methods could distinguish various debris types such as supraglacial debris, debris connected to glaciers and debris on high slopes. It is also found that more debris is accumulated at the origin of the Baltoro glacier system from 1990 to 2010. Rock avalanches might have 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 modified semi-automatic method is found to be more accurate, especially near the snout position and gives a similar result compared to manual and automatic approaches. Misclassification of Supraglacial lakes were also avoided by this method even though a part of horizontal debris is misclassified as non-supraglacial region. A recommendation is the use of up to date DEMs so as to monitor the region chronologically accurate. In automatic method, a threshold value is applied to the thermal waveband (TM6) and this raster is converted to and viewed as an shapefile to distinguish debris-covered glacier area from other topographic features. Further investigation using other images proved that, the choice of threshold value may vary with local weather conditions, cloud cover and snow cover and such applications are limited to images having very similar surface and seasonal characteristics. At the origin of the Baltoro glacier more debris accumulation is found in 2002 and 2010 compared to previous years. The chance of glacier expansion under the thickened supraglacial debris cover in 2002 and 2010 compared to 1990 and 1998 is higher but the presence of snow cover in some images caused difficulty in interpretation. 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. All these methods were found to give a comparable result with previous works (Mihalcea et al., 2008; Belo et al., 2008). When NDVI images were tested, it is seen that a there was a small shift occurred in the origin of Shigar River. The origin of the river has been taken as the snout position and it was found by visual inspection that the snout position has moved back from 1998 to 2002 which shows that the Baltoro glacier has undergone ablation during this period. The area of debris-covered glacier calculated using ArcGIS has shown that there was an overall increase in the glacier area.

Since the spatial resolution of Landsat imagery is low (30 m), misclassification due to mixed pixels may arise in debris cover maps. This limitation can be improved by using remotely sensed images of higher spatial resolution such as Rapideye and Worldview-2 during further research. Use of images and DEMs having higher temporal resolution is also expected to be effective in monitoring gradual changes. Surface temperature of debris-covered glaciers depends on debris thickness (Nakawo and Rana, 1999) and 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. 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. 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.

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