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RESEARCH ARTICLE

EVALUATION OF AUTOMATED AND MANUAL METHODS FOR MEASURING CHANGE IN KOLAHOI GLACIER USING GEOSPATIAL TECHNOLOGY

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ABSTRACT

Glaciers are the important components of earth's natural system and are sensitive indicators of climate change. Their accurate mapping and monitoring is inevitable for planning and management of water resources. Remote sensing and GIS has played an important role in mapping and monitoring of glaciers, considering their extent and inaccessibility. A number of methods using multispectral data are available, such as visual interpretation, band ratioing and spectral indices. An automated method (including spectral indices NIR/SWIR, NDWI, NDDI, TGM and Slope) was used for mapping various glacier terrain classes. Temperature and spectral difference between debris and non-debris covered parts of glacier enabled their differentiation by using different threshold values. The glacial extent derived from automated method was more accurate than that obtained from visual interpretation as it was capable of delineating debris-covered ice by incorporating thermal information. Thus automated method was accepted for delineating the change in Kolahoi glacier from 2001 to 2010. Trend analysis showed that the mean annual temperature (TMax and TMin) has increased and there is insignificant decrease in the total annual precipitation in the area. The rising temperature and declining precipitation might have contributed to the glacier recession in the area. However, anthropogenic activities like movement of Bakerwall tribe, pollution caused by the emission of greenhouse gases, military vehicular movement, cement plants and annual religious pilgrimage in the vicinity of glacier may also be expediting the recession of the glacier. Therefore, sound efforts need to be taken in order to save this precious source of water.

INTRODUCTION

A glacier or perennial snow mass consists of a body of ice and snow that is observed at the end of the melt season, or, in the case of tropical glaciers, after transient snow melts. This includes, at a minimum, all tributaries and connected feeders that contribute ice to the main glacier, plus all debris-covered part of it. Excluded all exposed ground, including nunitaks (Racoviteanu, 2008). As an integral part of cryosphere mountain glaciers constitute one of the most important components of the Earth's natural system and serve as sensitive climate-change indicators (Scherler *et al.,* 2011). Therefore, their accurate mapping and monitoring are of vital importance for the proper planning and management of water resources. Over the years, a number of remote sensing techniques for automated mapping of glacier snow and ice (GSI) by means of multispectral classification are available. Commonly used techniques for glacier-cover mapping include (1) band ratio techniques (Kääb, 2002; Paul *et al.,* 2013); (2) image classification techniques based on spectral indices (Keshri and others, 2009; Burns and Nolin, 2014; Bhardwaj *et al.,* 2015); (3) morphometric analysis of attributes such as slope, aspect and elevation (Bolch *et al.,* 2007; Shukla *et al.,* 2010); (4) multi-source and texture analysis (Paul *et al.,* 2004; Racoviteanu and Williams, 2012); and (5) supervised classification (Shukla *et al.,* 2009; Khan *et al.,* 2015). These research methodologies have mapped glacier facies with varying success and have been effective in distinguishing debris-free glacier ice from debris cover, but report difficulties in separating debris on the glacier surface from surrounding terrain (Shukla *et al.,* 2010; Racoviteanu and Williams, 2012). Spectral information alone is insufficient for debris-covered glacier mapping. Combining band ratios with topographic information is a promising approach for semi-automated mapping of debris-covered glaciers (Bandishoev *et al.,* 2011). For example, (Shukla and Ali, 2016) devised a semi-automatic approach called as hierarchical knowledge-based approach which used NIR/SWIR ratio and spectral indices such as normalized-difference glacier index (NDGI), normalized-difference water index (NDWI), normalized-difference debris index (NDDI), image transformations (intensity hue saturation (IHS) image), topographic attributes (slope) and the thermal glacier mask (TGM). This hierarchical knowledge-based approach was proposed for sequential differentiation of

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various glacier terrain classes, with particular emphasis on supraglacial debris (SGD), periglacial debris (PGD) and valley rock owing to their spectral similarity. Automatic classification of glaciers and GIS-based extraction of glaciers from Landsat TM data have been widely recognized as highly valuable methods for glacier mapping. Much of work has been done to analyze glacier changes using remote sensing techniques. A number of methods for mapping glaciers using multispectral data are available, such as visual interpretation, band ratioing and spectral indices. However, few studies have focused on comparison of different glacier mapping methods and selection of an appropriate mapping method. In this study, different spectral indices, band ratios and slope information were used to visually interpret the glacial extent. An unweighted overlay of all spectral indices, band ratios and slope was performed to delineate the glacial area and the results were compared with visually interpreted results. The relationships between glacier changes and trends of precipitation/temperature were also analyzed. The overall objective of this research is to quantify the changes of glacial area in space and time using different spectral indices and band ratios. The following are the specific research objectives:

- To estimate the glacier ice and debris-covered part of the glacier.
- To quantify glacier change by calculating changes in glacier area.
- To identify best method(s) for glacier mapping.

Study Area

The current study is focused on Kolahoi Glacier (34° 07′ to 34° 12′ N latitude; and 75° 16′ to 75° 23′ E longitude), in Liddar valley, Kashmir Himalayas, located at an altitude of 3690 m (Fig. 1). The meltwater stream of Kolahoi Glacier is known as the West Lidder River and joins the East Lidder River at Pahalgam (35km from the snout). Pahalgam is connected to Srinagar by road and from there to Aru (i.e. first 11 km). Beyond that, the remaining 24km to the glacier snout have to be covered either on foot or by pony (Ahmad and Hashmi, 1974). The glacier is ~5km long and has an area of ~11km^2. Its headwall is located at 5425m a.s.l. on Kolahoi Mountain, between the peaks of Dudnag in the west and Hiurbagwan in the east (Kaul, 1990). The Glaciers in the Lidder valley are presently confined along the northern ridge of the east and west Lidder valley. The glacier surface is marked by crevasses along the eastern margins of the ablation zone and an extensive mass of debris along the western margin (Kaul, 1990). Lidder is one of important tributaries of river Jhelum, formed by two mountain torrents (east and west Lidder).The Liddar valley has distinct climatic characteristics. It has sub-Mediterranean type of climate with nearly 80% of its annual rainfall in winter and spring season (Kanth *et al.,* 2011). Several glaciers radiate from Mt. Kolahoi, of which the largest is the main Kolahoi Glacier, flowing along the west and then the north-east side of the peak (Odell, 1963). Situated in the pahalgam village of Ananthnag district,the Kolahoi glacier is one of the most prominent hanging glacier in the Kashmir region (Ahmed and Hashimi,1974). The melting of this kolahoi glacier endangers the livelihood of almost two thirds of the population in the area surrounding it. This glacier forms the source for the River Jhelum, one of the prominent rivers in Kashmir, thus supporting the water demand for various purposes such as agriculture and horticulture.

MATERIALS AND METHODS

Dataset used: In this study, for monitoring glacier changes Landsat satellite datasets acquired in different years were chosen. Two scenes of different sensors, i.e. one from TM (October 2010) and one from ETM+ (September 2001), were obtained from the United States Geological Survey (USGS) web server (USGS – http://www.glovis.usgs.gov). Additional SRTM DEM scene was acquired from Earth Explorer web server (USGS- http://earthexplorer.usgs.gov/). Thus, it has been possible to monitor the glacial changes in the Kolahoi glacier from 2001 to 2010. In general, image selection for glacier mapping is guided by acquisition at the end of the ablation period, cloud-free conditions and lack of snow fields adjacent to glaciers (Paul 2004). According to these requirements, the Landsat data available for Kolahoi glacier were used for the study. Meteorological data comprising of air temperature (Tmax and Tmin), and rainfall from the year 2001 to 2010 have been used to see the changes in climatic conditions. This meteorological dataset was collected from Pahalgam station. Trend analysis of the meteorological data as carried out by (Murtaza and Romshoo, 2016) was used to see the changes in climatic conditions and the corresponding effect on the glacier fluctuations.

Methodology: In this study, current glacier distribution and glacier changes since 2001 were mapped using multi-temporal optical remote sensing data from the Landsat series. The utilized Landsat ETM+ and TM images are provided orthorectified with the methods defined by (Tucker *et al.* 2004) and therefore, matched well in their geolocation.

Pre-processing: Involved the conversion of visible, near infrared (VNIR) and shortwave infrared (SWIR) data to reflectance, and thermal data to brightness temperature. Details of these procedures are provided by Shukla *et al* (2010).The raw DN value images were converted to reflectance value images. However to calculate the brightness temperature thermal infrared band(s) were first converted to radiance from which brightness temperature was calculated. The brightness temperature was used to calculate the land surface temperature using Planck's radiation equation (Yin *et al.,* 2013). Finally, Landsat visible, SWIR, thermal bands and GDEM were resampled to 30m by nearest-neighbour interpolation in order to match the spatial resolution of the visible bands for band ratio computations.

***Automated method*:** Delineating the boundary of glacier from surrounding snow field and debris is the inevitable part of glacier mapping that requires several input layers (Fig.3): NIR/SWIR ratio and spectral indices NDWI, NDDI (Table 1), topographic attributes (slope) and TGM. The NIR/SWIR ratio image (Fig. 2a) was obtained from multispectral Landsat data for mapping of snow-ice. The normalized-difference snow index (NDSI) was also tested, but not used here as it misclassified water bodies as snow-ice, probably because of their similar bulk optical properties in the VNIR (Shukla and Ali, 2016, Dozier, 1989). The NDWI (Fig. 2b) facilitated the delineation of water (McFeeters, 1996). Many previous studies have applied band ratio algorithms for mapping of snow-ice, ice-mix debris and water, with satisfactory results (Paul *et al.,* 2004; Keshri *et al.,* 2009; Racoviteanu and Williams, 2012). TGM (Fig. 2c) and NDDI (Fig. 2d) were used to map the debris covered area of glacier (Shukla and Ali, 2016).

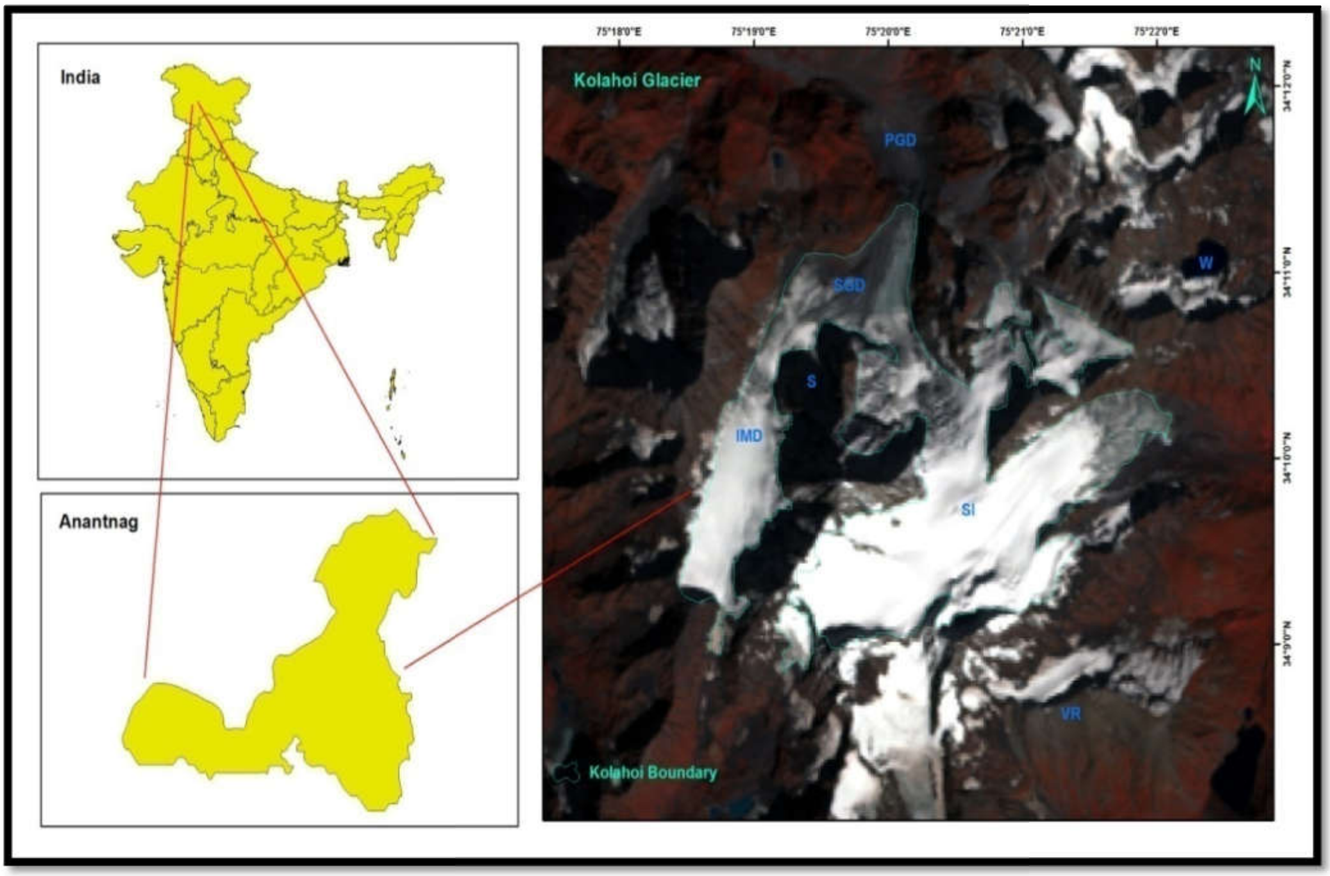

Fig. 1. The LANDSAT false-colour composite shows Kolahoi Glacier and the adjoining area, with band combination R = near-infrared, G = red and B = green band. In this map the abbreviations are W: water; SI: snow-ice; VR: valley rock; S: shadow; IMD: ice-mixed debris; PGD: periglacial debris and SGD: supraglacial debris

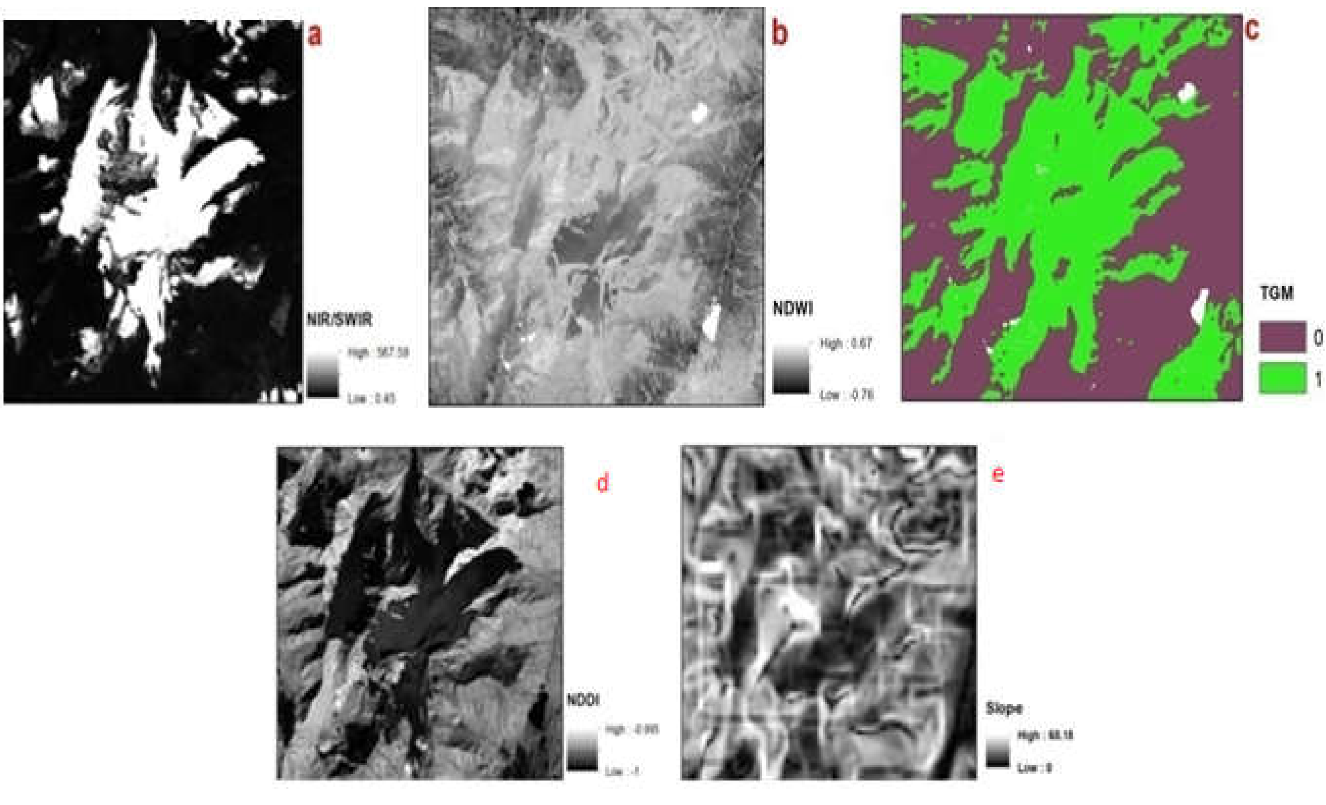

Fig.2. (a) NIR/SWIR (values 0–567.59); (b) normalized difference water index (values -0.76–0.67); (c); thermal glacier mask (TGM) (0: non-glacier area, 1: glacier area); (e) normalized-difference debris index (NDDI) (values -1–-0.995); and (f) slope map (values 0–68.18)

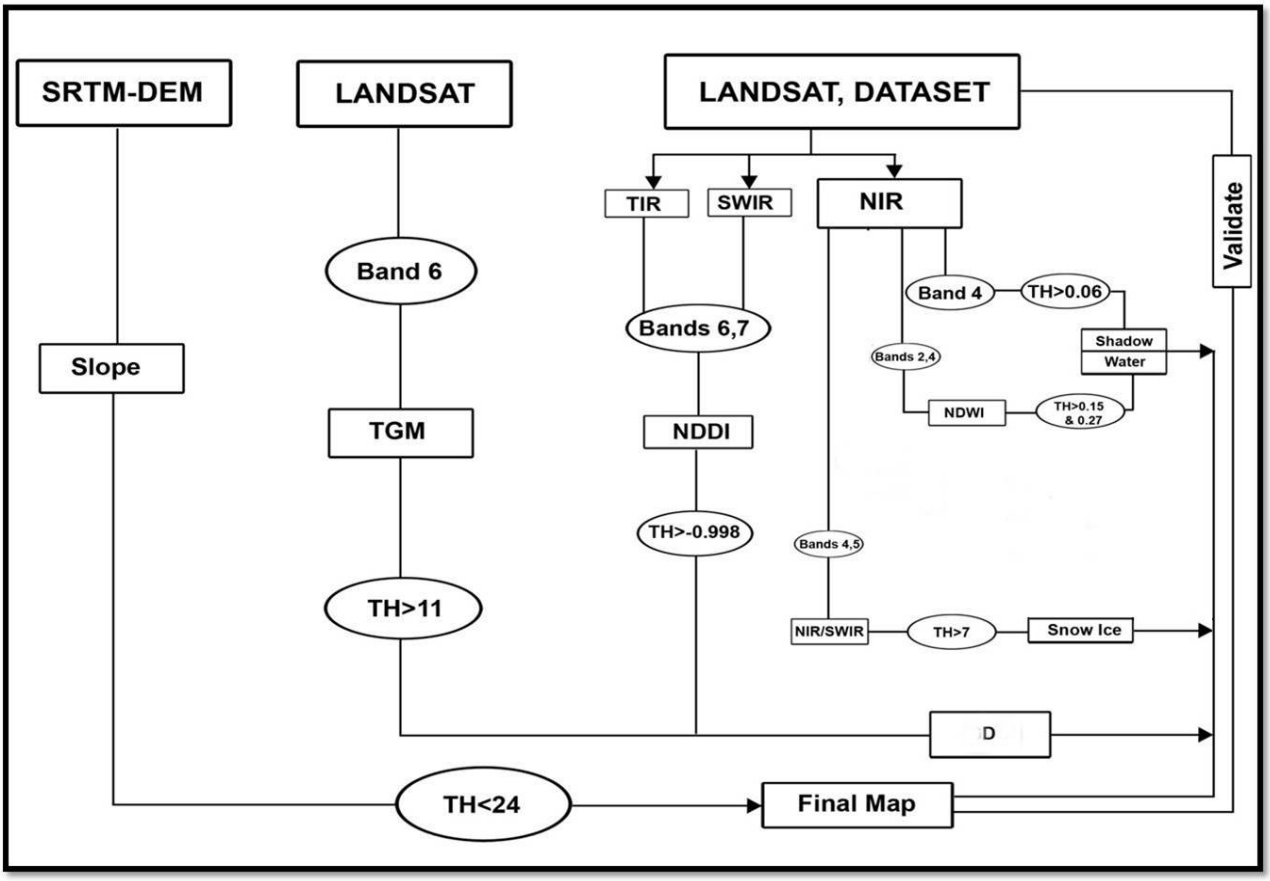

Fig. 3. Schematic diagram of automated approach

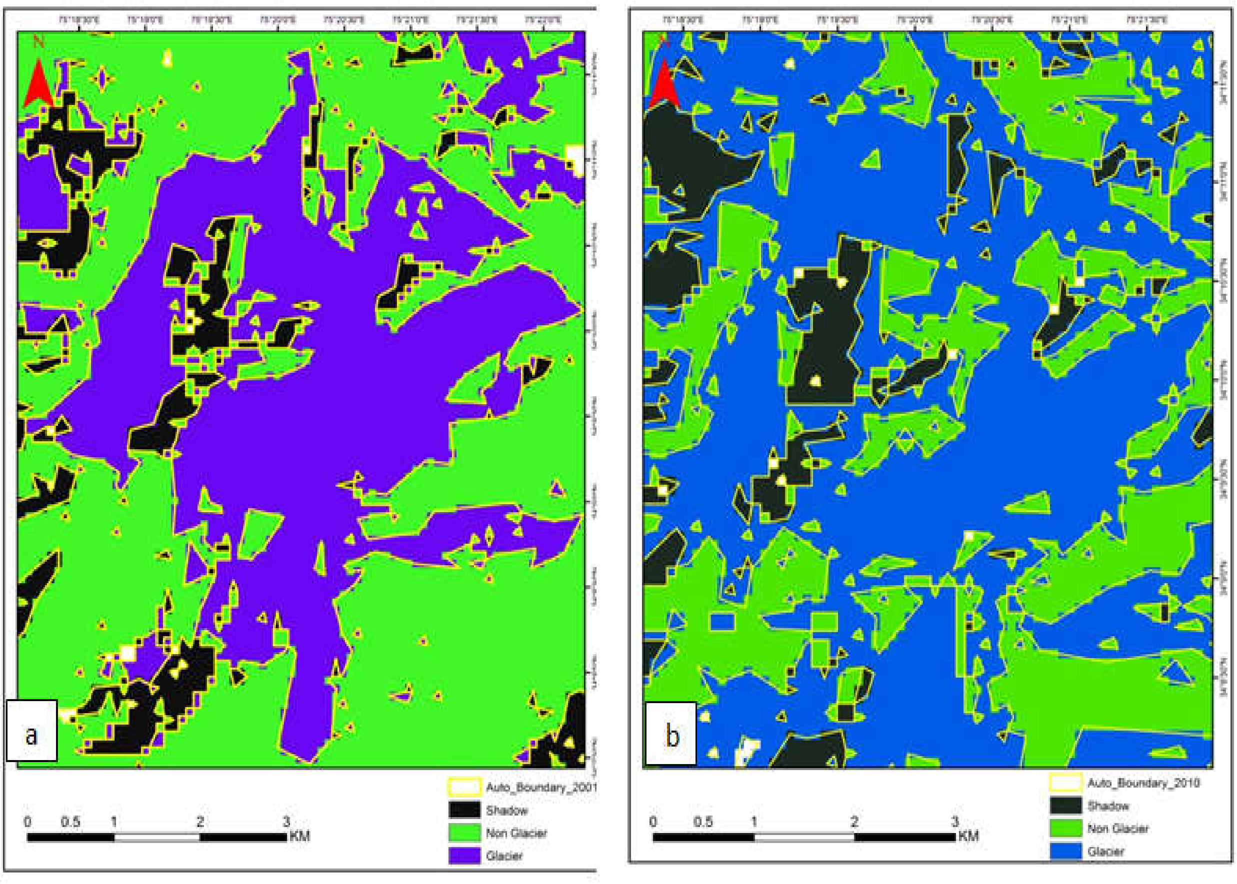

Fig.4. Glacial boundary derived from automated method

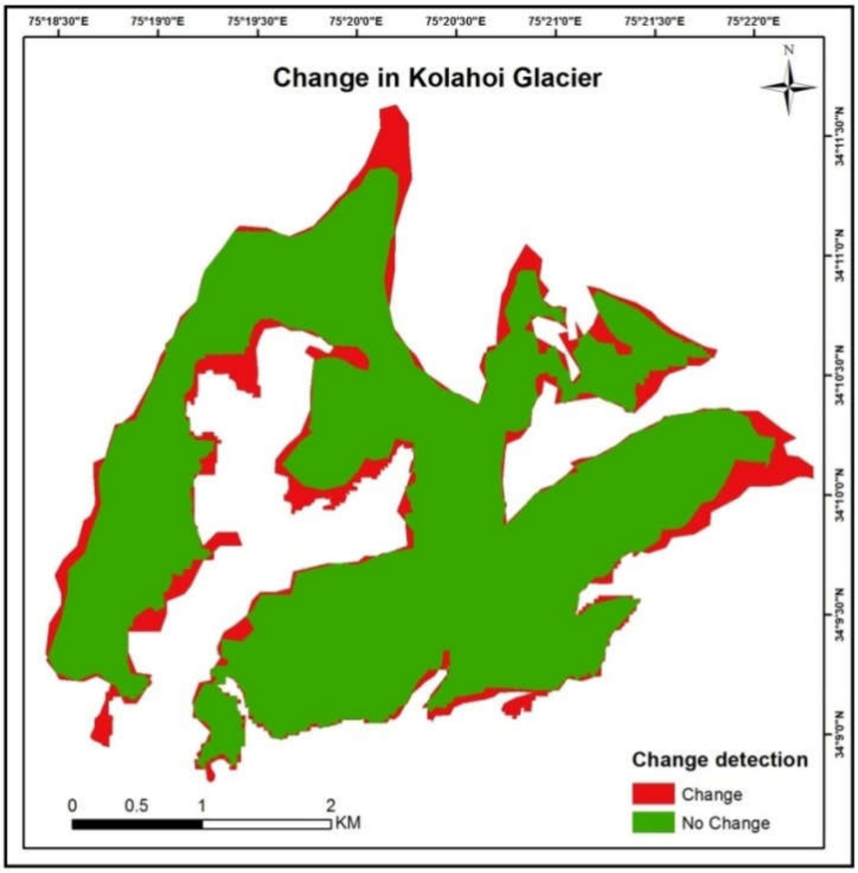

Fig. 5. Change in glacial extent from 2001 to 2010

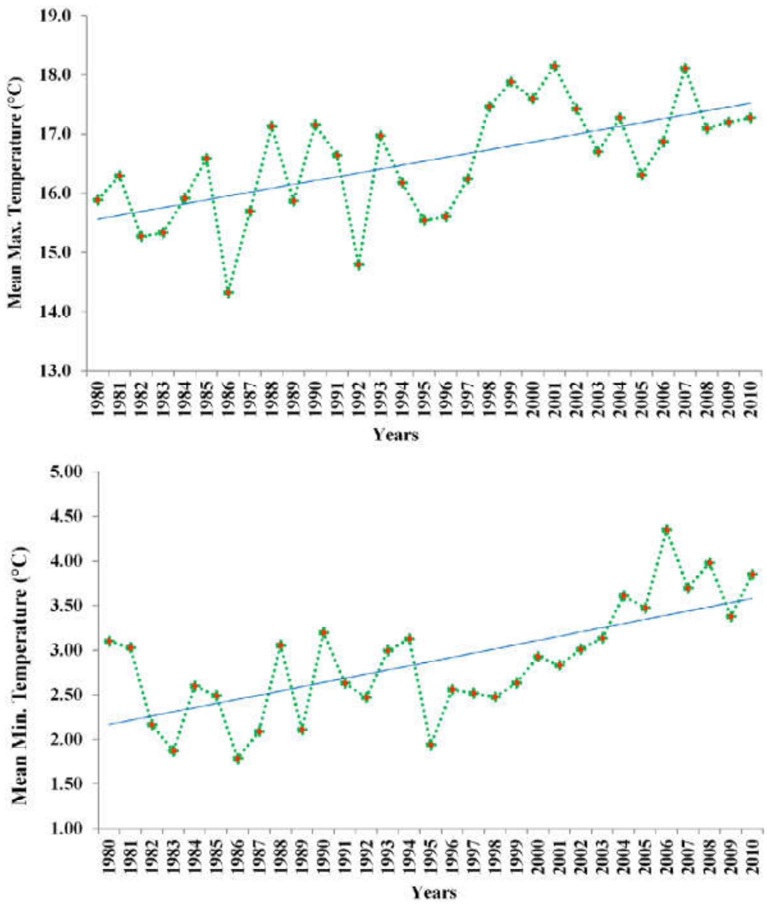

Fig. 6. Mean maximum and minimum temperature (°C) from 1980 to 2010. (Murtaza and Romshoo, 2016)

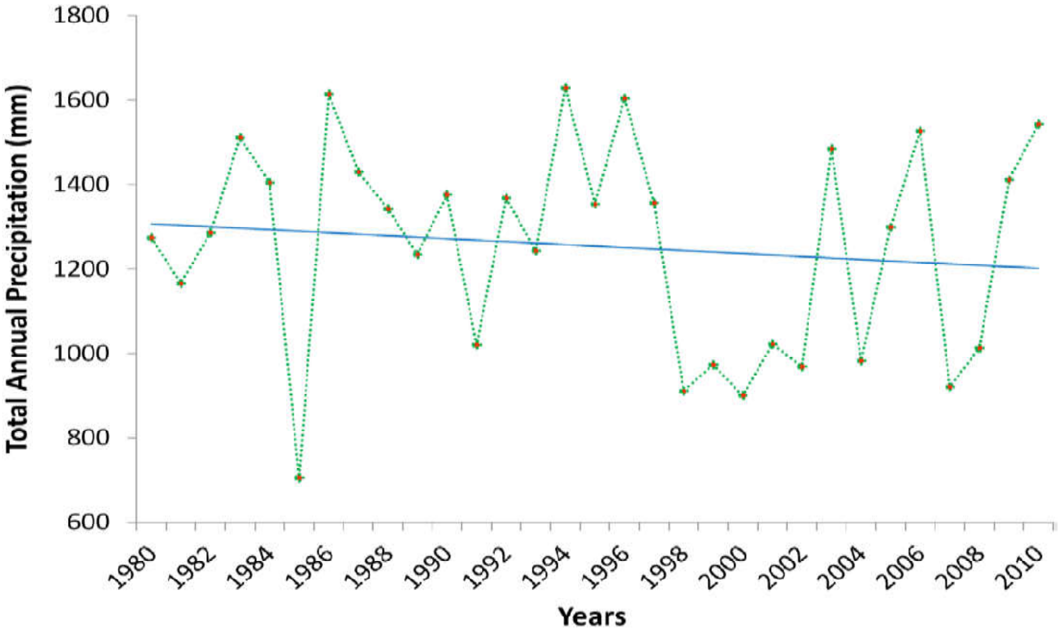

Fig. 7. Total annual precipitation (mm) from 1980 to 2010 (Murtaza and Romshoo, 2016)

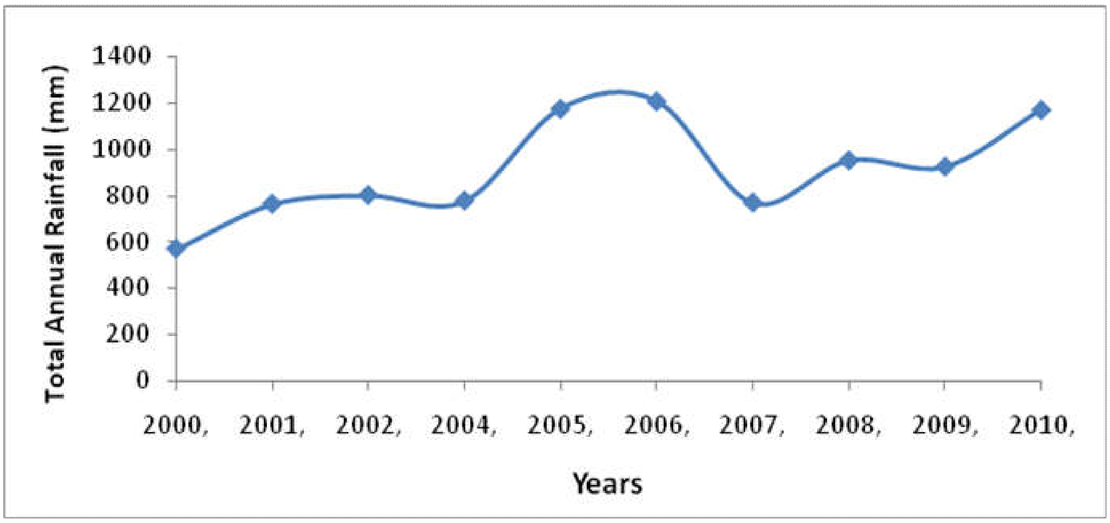

Figure 8. Total annual precipitation (mm) from 2000 to 2010

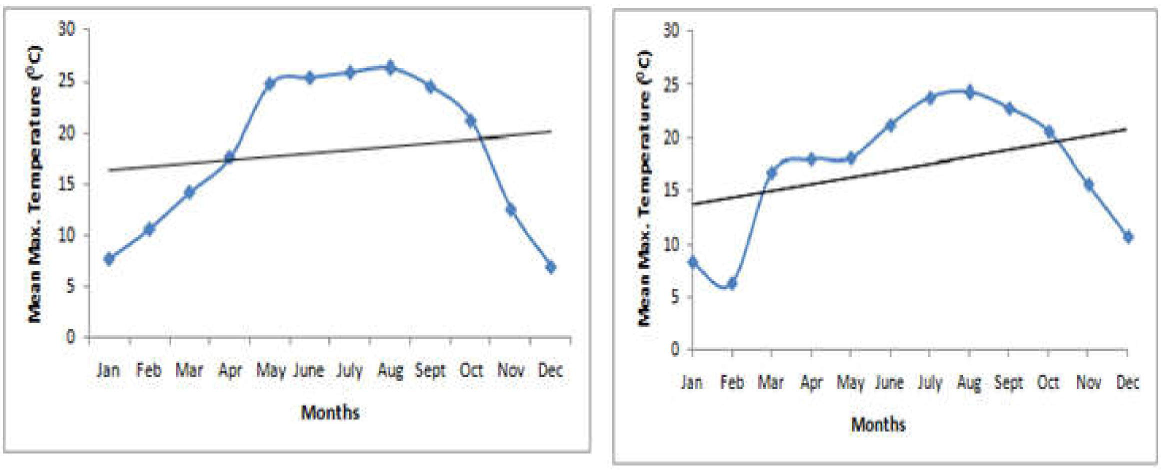

Fig.9. Mean maximum temperature (°C) for the year 2001 and 2010

Surface temperature of glacier cover classes viz snow-ice, debris differs considerably from non-glacier cover classes (Shukla and Ali, 2016). Therefore an in-depth investigation of surface temperatures was carried out and it was observed that the surface temperature of glacier cover classes does not exceed 11 degree centigrade. This criterion has been applied here for generation of a TGM, separating the classes with temperature below 11^0C as glacier cover classes (snow-ice and debris) from the classes with temperature above 11^0C as non-glacier cover classes (water and valley rock). The TGM so obtained is a binary map (TGM = 0 for non-glacier area and TGM= 1 for glacier area).The temperatures of the non-glacier cover classes in the shadowed regions were found to exceed those of glacier cover classes. This is in agreement with the results obtained by Shukla *et al* (2010) and Karimi *et al* (2012). A slope map (Fig. 2e) derived from the SRTM facilitated the separation of debris and no-debris area.

Detailed steps used in Automated method The individual steps followed for mapping different glacier terrain classes are described here:

The methodology applied for automated mapping of glacier extent has been taken from (Shukla and Ali, 2016). The rationale behind the steps outlined by (Shukla and Ali, 2016) remained same, although the thresholds applied to derive the final results varied based on scene. The processing workflow is schematically shown in Fig. 3.

Shadow and water: The shadowed regions were classified using Landsat band 4, using a threshold value of 0.06 (band 4 < 0.06 = shadow). This helped to reduce misclassifications among glacier terrain classes. Shukla and Ali (2016) adopted a similar approach to remove shadowed regions. Similarly, water was differentiated by NDWI, applying a threshold of 0.15 for ETM+ sensor (NDWI < 0.15= water) (Fig. 2a) and 0.27 for TM sensor.

Snow-ice: NIR/SWIR ratio image was used to map the snow-ice (Shukla and Ali, 2016). A threshold value of 7 (NIR/SWIR > 7 = snow-ice) was found to be suitable for snow-ice (Fig. 2a).

Debris and Valley rock: Debris covered regions has a slope range of 0–24°. (Shukla and Ali, 2016); (Paul and others, 2004; Karimi and others, 2012), suggest that most of the debris-covered regions can be captured at this slope threshold since debris tends to rest on gentler slopes. Thus, a threshold value of 24^0 was used to map debris covered and areas with no debris (slope < 24° = debris, else valley rock) (Fig. 2f).

Debris: Debris in the study area was mapped using TGM and NDDI (Shukla and Ali, 2016). The threshold used for NDDI was -0.998 (Fig. 2d) (TGM = 1 or NDDI > -0.998 = D). TGM was able to classify those regions as debris where NDDI could not map it and vice versa (Shukla and Ali, 2016). After mapping different glacier terrain classes, the glacier area and boundary was delineated by overlaying all the above generated results (Fig. 4).

Manual Approach: The manual delineation of debris-covered glaciers is time consuming and the accuracy depends on the expertise of the user. This is a traditional method for quantitative assessment of glacier change (area/length) (Paul, F., et.al, 2004). In this method, the false colour composite images (FCC) from Landsat ETM+ and TM of the year 2001 and 2010 respectively, were visually examined and the glacial extend was digitized manually. The method was found unsuitable for mapping the exact boundary of the glacier as the debris covered part of the glacier could not be included using only FCC images.

RESULTS AND DISCUSSION

Automated and Manual approach: Two approaches (Automated and Manual) were used for mapping extent of Kolahoi glacier. The automated approach for delineating the glacial area included different image indices and segmentation techniques (Table 1 and Fig. 2). The results obtained from different indices were finally overlaid to map the glacial extent and boundary (Fig. 4). The efficiency of the automated method was evaluated against the manually digitized boundary of the glacier. The automated approach proved effective in mapping glacier terrain classes, especially where glaciers were accompanied by varying amounts of debris in their ablation areas (Shukla and Ali, 2016). The boundary derived from automated method neither simply follows the ice margins nor depends solely on the optical spectral properties of debris cover. It maps the glacier boundary including the hidden ice beneath the debris cover (Shukla and Ali, 2016). To map the extent of Kolahoi glacier by on-screen digitization (manual approach) false-colour composite (FCC) images were visually examined, while the boundary delineated by visual interpretation relies mostly on the optical properties of the debris, thus has least accuracy. Hence automated approach was accepted for finding change in Kolahoi glacier along with meteorological data analysis.

Glacial area change: During Pleistocene, Kolahoi glacier was fed by nine other glaciers and its basin covered about 650km². The present snow field feeding this glacier covers only 2.5km², and no other glacier joins it. In Pleistocene it extended for 35km to terminate near 2760m ASL and at present it terminates within 3 km from its cirque at 3650m ASL (Ahmad and Rais, 1998). The present study revealed that the Kolohai glacier shows recession in terms of spatial extent and variations in the terminus of the glacier. From the comparison of the calculated glacier area from the multi-series satellite data it was observed that the glacier extent has decreased with the passage of time. In the present study change detection was carried from 2001 to 2010 as given in table 2 and depicted in fig.5. The area under Kolahoi glacier in the year 2001 was 11.75 km^2 that has retreated up to 10.40 km^2 in the year 2010, which is a decrease of about 1.35 km^2 in 9 years.

The rate of change from the year 2001 to 2010 is 0.15 km^2, thereby showing a clear deglaciation in the Kolahoi glacier. (Rashid, A., *et al.,* 2015), have also found the same area of Kolahoi glacier for the year of 2001. The causes for this receding trend can be both anthropogenic and natural like temperature increase, deforestation, tourism, increased activity of Gujjars and Bakerwalls (Tribal communities), high levels of pollution caused by the emission of greenhouse gases, military vehicular movement, cement plants, etc. (Kanth *et al.,* 2011). The Crevasses developed in the ablation portion of the Kolahoi Glacier and the formation of numerous caves at its snout position act as the important indicators of its recession (Kanth *et al.,* 2011).

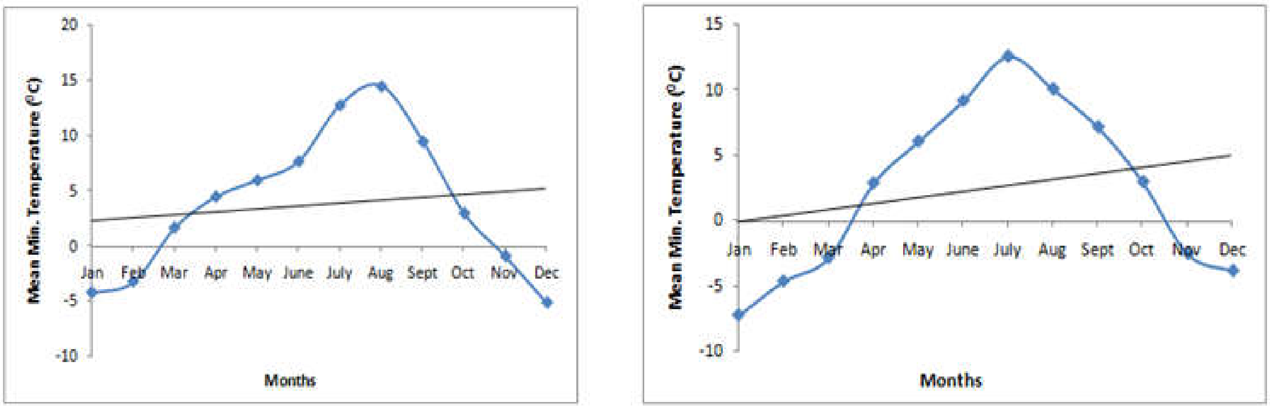

Fig.10. Mean minimum temperature (°C) for the year 2001 and 2010.

Table 1. Description of the spectral indices discussed in this study

Spectral index	Source	Formulation	Utility
Normalized-difference snow index (NDSI)	Dozier (1989)	$Green_{b2} - SWIR_{b7} / Green_{b2} + SWIR_{b7}$	Mapping and differentiating between snow-ice covered areas and non-snow-and-ice areas
Normalized-difference debris index (NDDI)	Shukla and Ali (2016)	$SWIR_{b7} - TIR_{b6} / SWIR_{b7} + TIR_{b6}$	Mapping and differentiating between supraglacial debris and that of the terrain
Normalized-difference water index (NDWI)	McFeeters (1996)	$Green_{b2} - NIR_{b4}$ / Green2 + NIR4	Mapping surface water

Table 2. Change Detection of Kolahoi Glacier. (Source: Computed from Landsat ETM+, 2001 & Landsat TM, 2010)

Area(Km^2) 2001	Area(Km^2) 2010	Time Interval	Change (Km^2)	Rate of Change (km^2/year)
11.75 Km^2	10.40 Km^2	9 years	1.35 Km^2	0.15 Km^2

The recent rise in the pilgrim rush to Amarnath Cave and increased time duration of pilgimage may also be a significant cause in the recession of Kolahoi glacier. Further, use of helicopter from past few years to ferry pilgrims may be a major cause in the formation of caves and crevasses. Besides the emitted green house gases, the dust, black carbon and chemical pollutants also form the major influential factors contributing to the rise in the Himalayan temperatures (Meehl 2008). Aerosols, deforestation and forest fires form the major source for the augmentation of the dust and black carbon, while the chemical pollution is mainly due to the human induced pollution (Raina 2009). The winter low temperatures are necessary for the accumulation of snow and subsequent development of the glaciers, where as the low summer temperatures are necessary for preventing the rapid melting of the glaciers. The monthly mean temperatures for summer and winter are showing higher rate of increase and resulting retreating processes of the glacier in the region (Islam et,al, 2008).

Meteorological data analysis: The trend analysis was carried out by (Murtaza and Romshoo, 2016) for the mean annual temperature (T_{Max} and T_{Min}) and the total annual precipitation (1980–2010) from the meteorological data available from Pahalgam Station. They have found a gradual increase in average minimum temperature and average maximum temperature with interannual fluctuations during the observation period (Fig. 6). The most significant evidence for regional and global climate change is the increase in minimum temperature. Lidder valley receives precipitation both in the form of snow and rainfall. Precipitation (Fig.7) showed decreasing but statistically insignificant trend during the observation period (Murtaza and Romshoo, 2016). Their analysis of the climate data reveals that the glacier fluctuations have correlation with the observed changes in the air temperature and precipitation. The significant increase in the temperature (T_{min} and T_{max}) and small decrease in the precipitation over the area may have attributed to increased ablation and less accumulation resulting in the observed glacier changes (Murtaza and Romshoo, 2016). The variation in precipitation (Fig. 8) is statistically insignificant and mean maximum temperature trends (Fig. 9) are almost similar in both the years 2001 and 2010 while the mean minimum temperature shows a slight increase especially during the end of hydrological year (Fig. 10). The Indian Himalayan region, including Kashmir, is facing a change in the form of precipitation from solid to liquid phase which has been described as one of the significant factors responsible for less accumulation of snow on glaciers (Thayyen *et al*. 2005; Dimri and Mohanty 2007; Romshoo *et al*. 2015). In the Himalayas, the rise in the average temperature during winter months has brought a change in the precipitation pattern with December and January months now receiving scanty snowfall while February and March are witnessing relatively more snowfall (Dar *et al*. 2014; Mir *et al*. 2014). An increase in the temperature is usually accompanied by a decreasing trend in precipitation, and a reduction in the total seasonal snowfall (Shekhar *et al*. 2010; Dar *et al*. 2014) which might have made a profound negative impact on the glacier health in the region (Murtaza and Romshoo, 2016). Temperature and precipitation are the two major climatic variables affecting the ablation and accumulation characteristics of glaciers (Murtaza and Romshoo, 2016). The rise in temperature has rendered the snow incapable of freezing into long lasting crystal layers, resulting in a decline in the mass of the glacier. An important link between the changing climate and glacier retreat has been reported in various studies carried out during the last century (Hasnain 2002; Haeberli 2005; Kaser *et al*. 2006; Romshoo *et al*. 2015).

Conclusion

The present study was aimed at analysing the fluctuations in Kolahoi glacier using Landsat series datasets. In this study, automated method was used for mapping various glacier terrain classes. NIR/SWIR and NDWI clearly discerned snow-ice and water respectively. Debris and valley rock were discerned by using NDDI, TGM and slope images. The glacial boundary derived from automated method was more accurate than that obtained from visual interpretation as it was capable of delineating debris-covered ice by incorporating thermal information (Shukla and Ali, 2016). Thus automated approach was accepted for delineating the change in glacier area from 2001 to 2010. Mapping the changes in the glacier extent of Kolahoi glacier revealed that the glacier has receded in its areal extent during the last 9 years (2001 to 2010). The area under Kolahoi glacier in the year 2001 was 11.75 km^2 that has retreated up to 10.40 km^2 in the year 2010, which is a decrease of about 1.35 km^2 in 9 years. The rate of change from the year 2001 to 2010 is 0.15 km^2, thereby showing a slight deglaciation in the Kolahoi glacier. Trend analyses showed that the mean annual temperature (T_{Max} and T_{Min}) has increased and there is insignificant decrease in the total annual precipitation in the area. The rising temperature and declining precipitation might have contributed to the glacier recession in the area. Also, the anthropogenic activities like Bakerwalls, high levels of pollution caused by the emission of greenhouse gases, military vehicular movement, cement plants and annual religious pilgrimage in the vicinity of glacier may also be expediting the recession of the glacier. Nevertheless, the steady depletion of the glacier is very evident from this study and if this trend of recession continues, it may affect water availability for irrigation, hydropower generation, horticulture and recreational use in the region. Thus, constructive steps should be taken by the government agencies to ensure the longevity of the glacier as a precious source of water.

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