INTEGRATED APPROACH FOR MAPPING DEBRIS-COVERED GLACIERS USING OPTICAL, THERMAL AND TOPOGRAPHIC INFORMATION-A CASE STUDY ON BARA SHIGRI GLACIER, WESTERN HIMALAYA, INDIA

Swagata Ghosh[1,] and RAAJ Ramsankaran[2, 3]
[1]Amity Institute of Geoinformatics and Remote Sensing (AIGIRS), Amity University-Sector 125-Noida-201303, UP, India,
E-mail: swagata.gis@gmail.com; sghosh1@amity.edu

[2]Department of Civil Engineering, Indian Institute of Technology Bombay, Powai-400076, Mumbai, Maharashtra, India
[3]Inter-disciplinary Program in Climate Studies, Indian Institute of Technology Bombay, Powai-400076, Mumbai, Maharashtra, India,
E-mail: ramsankaran@civil.iitb.ac.in

KEY WORDS, Debris-covered Glaciers, Supraglacial covers, Supraglacial debris, Himalaya, Landsat-8.

ABSTRACT: Supraglacial debris strongly influences the rate of ablation of a glacier and thereby effecting the health and the contribution of the glaciers towards surface runoff. Moreover, debris cover over the ablation zone of the glaciers hampers automated and semi-automated mapping of glacier boundaries in different parts of the Himalayan region. Therefore, the present study proposes an integrated approach for delineation of glacier boundaries and supraglacial cover mapping of debris-covered glaciers using Landsat-8 OLI (Operational Land Imager) and TIRS (Thermal Infrared Sensor) image and Digital elevation model (DEM). The proposed approach has been tested for delineation of the boundary of Bara Shigri Glacier, an extensively debris-covered glacier of Himachal Pradesh. Results obtained using the proposed approach correspond well with manually demarcated glacier boundary using a high resolution Linear Imaging Self Scanner (LISS)-IV image. Moreover, the proposed integrated knowledge based classification (KNC) technique is observed to be faster than the manual delineation in delineating the debris covered glacier boundary.

1. INTRODUCTION

Glacier health is an important indicator of climate change and sensitive to their surrounding environmental change. Throughout the world, decline in glaciated area and its diverse impact has given rise to the global interest to fill the gap in monitoring and mapping of the Himalayan glaciers (Cogley, 2011). In remote and unapproachable regions like the Himalayas, remote sensing-based glacier mapping is proved as an efficient way of monitoring glaciers. (Berthier et al., 2007; Kulkarni et al., 2005; Kulkarni et al., 2007). Many Himalayan glaciers are covered with debris in the lower ablation zone. Mapping of such debris-covered glacier boundaries even by remote sensing has always been a challenge due to the presence of supraglacial debris (debris over the glacier) since it has similar spectral properties than that of periglacial debris (debris outside glacial boundary) (Bolch et al., 2007; Shukla et al., 2010).Therefore, many studies have been conducted for mapping of debris-covered glacier boundaries through manual delineation (Berthier et al., 2007; Ghosh et al., 2014; Kulkarni et al., 2005, 2007; Pandey et al., 2011), multi-spectral optical information based techniques by utilizing supervised classification scheme (Shukla et al., 2009), band ratio (Keshri et al., 2009), combination of different spectral indices (Minora et al., 2013), Geomorphometric-based techniques utilizing slope, aspect and curvature of debris cover areas (Bolch et al., 2007), thermal techniques based on difference in thermal characteristics of supraglacial debris and periglacial debris (Ranzi et al., 2004; Taschner and Ranzi, 2002), combination of spectral, geomorphic and thermal information (Paul et al., 2004; Bhambri et al., 2011; Karimi et al., 2012; Shukla et al., 2010; Shukla and Ali, 2016). Literature review suggests that semi-automated methods i.e. sequential classification of glacier using both morphometric parameters and the thermal information has a great potential in mapping the debris-covered glaciers. However, it requires a lot of time and we need to sequentially proceed to get the final output map. Looking into the complexities in the mapping of debris covered glaciers and immense role of supraglacial debris on the process of ablation of glaciers (Scherler et al., 2011), in this study we propose an integrated Knowledge based classification (KNC) approach. KNC is a new and advanced classification method in which various data sources can be integrated by forming simple production rules.

2. STUDY AREA

The study area (Fig. 1) constitutes the Bara Shigri glacier located in the Chandra sub-basin (Chenab basin), in Himachal Pradesh. It extends from Latitude 32° 5′N to 32° 18′N and Longitude 77° 32′E 77° 49′E. The elevation range of the study glacier varies from 3881 to 6582 m above sea level. Bara Shigri glacier is one of largest glacier in western Himalaya covering an area of 121km^2 in 2014. The glacier is fed by numerous tributary glaciers. More than 10% of the glacier area is debris covered. Supraglacial debris can be seen from the vicinity of the snout up to the upper ablation zone as shown in Figure 1.

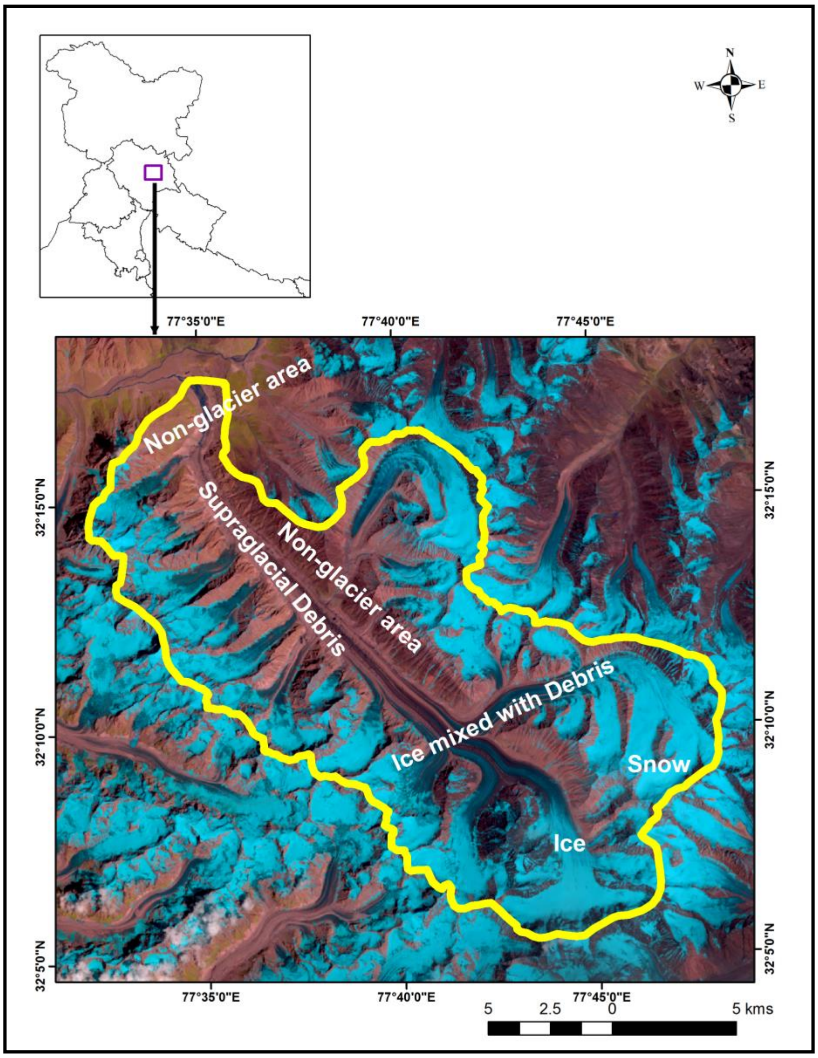

Figure 1: Overview of the study area- Bara Shigri glacier located in the Chandra sub-basin (Chenab basin), Himachal Pradesh on Landsat-OLI image of August 11, 2014 (a false colour composite with band combination, R=Shortwave Infrared (SWIR1) band, G=Near Infrared (NIR) band, and B=Red band) with the distribution of supraglacial covers.

3. DATA USED

In this study Landsat 8 Operational land imager (OLI) cloud free image and Thermal infrared sensor (TIRS) image acquired on 11th August 2014 (Image id: LC81470382014223LGN01; Path/Row-147/38) and ASTER Global Digital Elevation Model (GDEM V2) (Image id: ASTGTM2_N32E077) downloaded from the United States Geological Survey (USGS) server were used. For mapping purpose, OLI bands (Band1 to Band7 and Band9) have been used to extract the Top of atmospheric (TOA) reflectance of various supraglacial cover types and TIR band (Band 10) has been utilized to extract the brightness temperature. ASTER GDEM has been used to derive the slope and elevation map of the study area. Finally, to verify the glacier boundary delineated using the integrated approach, the terrain-corrected high-spatial resolution (5.8m) scene (image id:163904811;Path/Row-95/48) of Indian Remote Sensing Satellite (IRS)-Resourcesat 2 Linear Imaging Self Scanner (LISS)-IV multi-spectral sensor has been used.

4. METHODOLOGY

The entire methodology (Fig. 2) to identify the supraglacial covers and thereby delineate the debris-covered glacier boundary is comprised of the following steps.

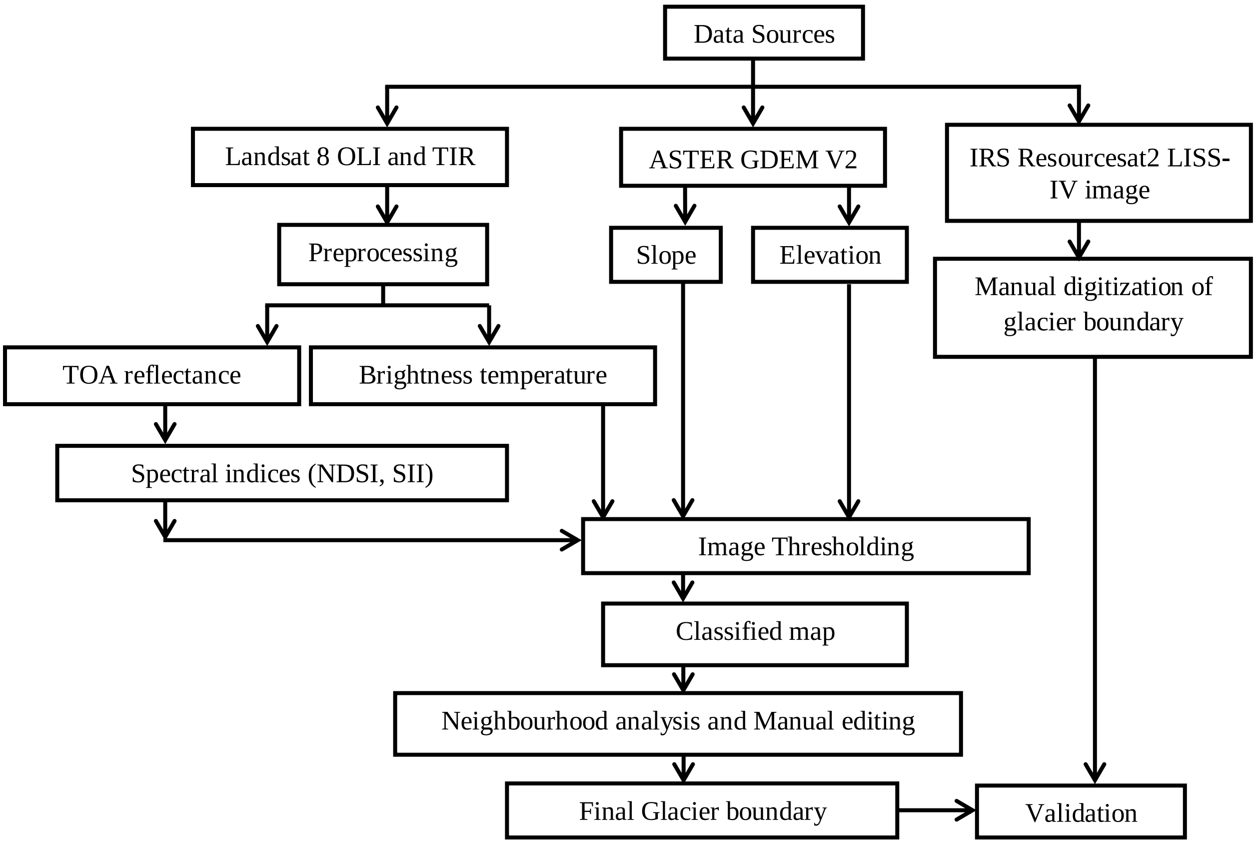

Figure 2: Flowchart of the methodology.

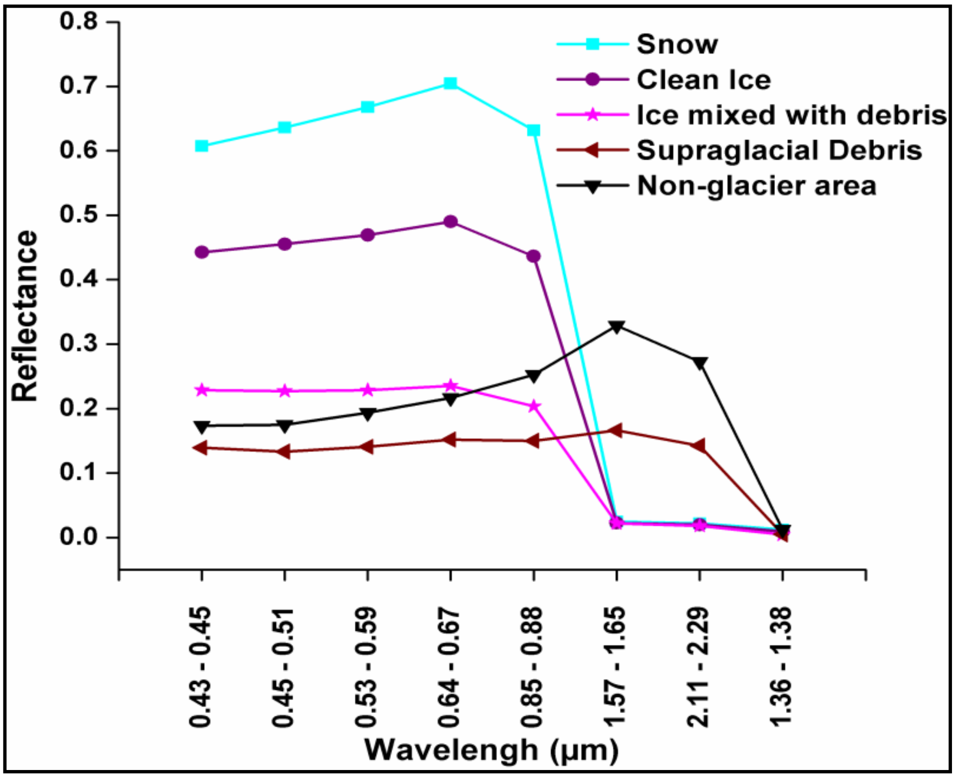

Figure 3: Spectral reflectance curves for supraglacial covers, derived from OLI image of 2014.

In the present study, an integrated classification approach has been carried out for categorization of supraglacial covers and delineation of glacier boundary using the spectral, temperature, slope and elevation information. The entire analysis has been performed in Eradas Imagine 2014, a remote sensing image processing software. For carrying out the classification approach, OLI and TIRS digital number (DNs) have been converted to TOA reflectance and 'at-satellite brightness temperature' respectively. ASTER GDEM V2 has been used to derive the slope and elevation map of the study area. To select an appropriate threshold value for each parameter, areas of interest (AOIs) on the desired class have been drawn based on visual inspection of the Landsat-OLI standard FCC and the output images for each spectral index (Normalised Difference Snow Index, Snow Ice Index) images, 'at-satellite brightness temperature' image, slope and elevation maps. On the basis of spectral behaviour of different types of supraglacial covers (Fig. 3), Normalized Difference Snow Index (NDSI) using the Green and SWIR1 band has been used initially to discriminate snow and ice from other land cover types (non-snow area).The areas covered by snow and ice (snow + clean ice + ice mixed with debris) in the reflectance image of OLI have been extracted by identifying the pixels having NDSI value > 0.6. The waterbodies (which are supposed to be classified as non-snow area) present in the lower ablation zone over the supraglacial debris have been misclassified as snow-ice.

To differentiate between snow, clean ice and ice mixed with debris, the spectral characteristics of these three supraglacial covers have been analyzed in Red bands and SWIR1 band (Fig. 3). The high reflectivity in the visible region and comparatively low reflectivity in SWIR region for all three supraglacial covers have been observed. In the Red band, the reflectance percentage is highest for snow followed by clean ice and ice mixed with debris respectively. In the SWIR band, reflectance percentage is quite similar for these three supraglacial covers. Looking into such spectral signatures, simple ratio of Red band and SWIR1 band is designed and applied on the areas covered by snow and ice (snow + clean ice + ice mixed with debris) in the reflectance image of OLI. As the reflectance percentage of snow in Red band is very high compared to ice (Clean ice + Ice mixed with Debris), the simple ratio (Red / SWIR1) value is expected to be very high in case of snow compared to ice (Clean ice + Ice mixed with Debris). But being the shorter wavelength, Red band is more affected by scattering compared to SWIR1. Furthermore, due to the physical properties, snow is more sensitive to scattering compared to ice. As a result, the reflectance percentage is lesser than expected in case of snow in Red band and therefore, the simple ratio (Red / SWIR1) value becomes lower than expected value in case of snow in some places of the accumulation zone having higher slope and elevation. Moreover, the detailed analysis of the spectral signatures of supraglacial covers revealed that reflectance percentage of snow is different (higher) than ice even in case of SWIR1 band. Such minor difference in reflectance percentage is not clearly evident in Figure 3 (as the reflectance percentage of all supraglacial covers are represented in same scale). Therefore, the simple ratio (Red / SWIR1) value for both snow and clean ice is too close and threshold value selection is not possible. Resultantly, simple ratio (Red / SWIR1) value is not able to discriminate between snow and clean ice in those places of the accumulation zone. To avoid the scattering effect and increase the range of pixel values, the simple ratio (Red / SWIR1) is further divided by SWIR2 (being the longer wavelength, SWIR 2 is not much affected by scattering) as given in Equation 1.

$$SnowIceIndex\ (SII) = \frac{[Red/SWIR1]}{SWIR2} --------------(1)$$

Eq.1 has been applied on the image of snow and ice. Finally, 'ice mixed with debris', 'ice' and 'snow' has been classified by identifying the pixels having the SII value ≤ 0.27, 0.27 < SII value ≤ 0.51 and SII value > 0.51 respectively.

After the segregation, it was found that the waterbodies present in the lower ablation zone and very few pixels in the stream emerging from the snout of the Bara-Shigri glacier have been misclassified as 'ice mixed with debris'. Therefore, to remove such misclassification, the topographic parameter and a threshold value of 'Elevation> 4600 m' has been used. This elevation threshold is selected because all the waterbodies are present below the elevation of 4600 metres. In this way, 'waterbodies' are excluded and such misclassification is avoided.

In the study site, non-glacier area mainly includes periglacial debris, steep rocky area and water. For segregating these non-glacier areas from supraglacial debris, an image representing the other land cover types ('supraglacial debris' + 'non-glacier area') has been created from the reflectance image by identifying the pixels having NDSI value ≤ 0.6. Unlike non-glacier area, supraglacial debris is underlined by glacier ice acting as a cooling source. Therefore, existing temperature difference between supraglacial debris and surrounding non-glacier area (Ranzi et al. 2004; Taschner and Ranzi 2002) has been successfully used to discriminate each other (Mihalcea et al. 2008). In the present study, temperature values ≤ 23° have been selected as threshold. However, in some places rocky areas at higher elevation with low temperatures has been misclassified as 'supraglacial debris'. To remove such misclassification, slope values ≤ 15° have been used. Yet, the stream and its adjoining area emerging from the snout of the Bara-Shigri glacier have been misclassified as 'supraglacial debris'. To eliminate the misclassification, Elevation > 4050m has also been utilized, as the presence of supraglacial debris of the glacier starts from the snout upto the middle ablation zone. Therefore, elevation can be used as the contributing parameter to remove the misclassification exists in the elevation zone lower than the snout elevation. Finally, Equation 2 has been used for identifying the supraglacial debris

IF((NDSI $\leq$ 0.6) AND (Brightness temperature $\leq$ 23°C) AND (Slope $\leq$ 15°) AND (Elevation > 4050))THEN 'supraglacial debris'-- (2).

Finally, after the vectorization of the classified map, neighbourhood analysis and minor manual editing have been performed to exclude those areas not connected with the main glacier body to delineate the boundary of the Bara-Shigri glacier.

5. RESULTS AND DISCUSSIONS

The glacier boundary obtained using the proposed approach and the boundary obtained through manual digitization of high resolution IRS LISS IV image are shown in Figs. 4 a and b. Figure 4a shows the boundary of Bara-Shigri glacier obtained before neighbourhood analysis and manual editing using the proposed integrated approach overlaid with the manually delineated boundary using high-resolution LISS-IV image. At this stage, the snout of the glacier is identified accurately (enlarged view of Fig. 4a (i)). However, after detailed evaluation and comparison, discrepancies are identified in the obtained boundaries of the glacier as shown in Fig. 4a (ii). Initially, in the

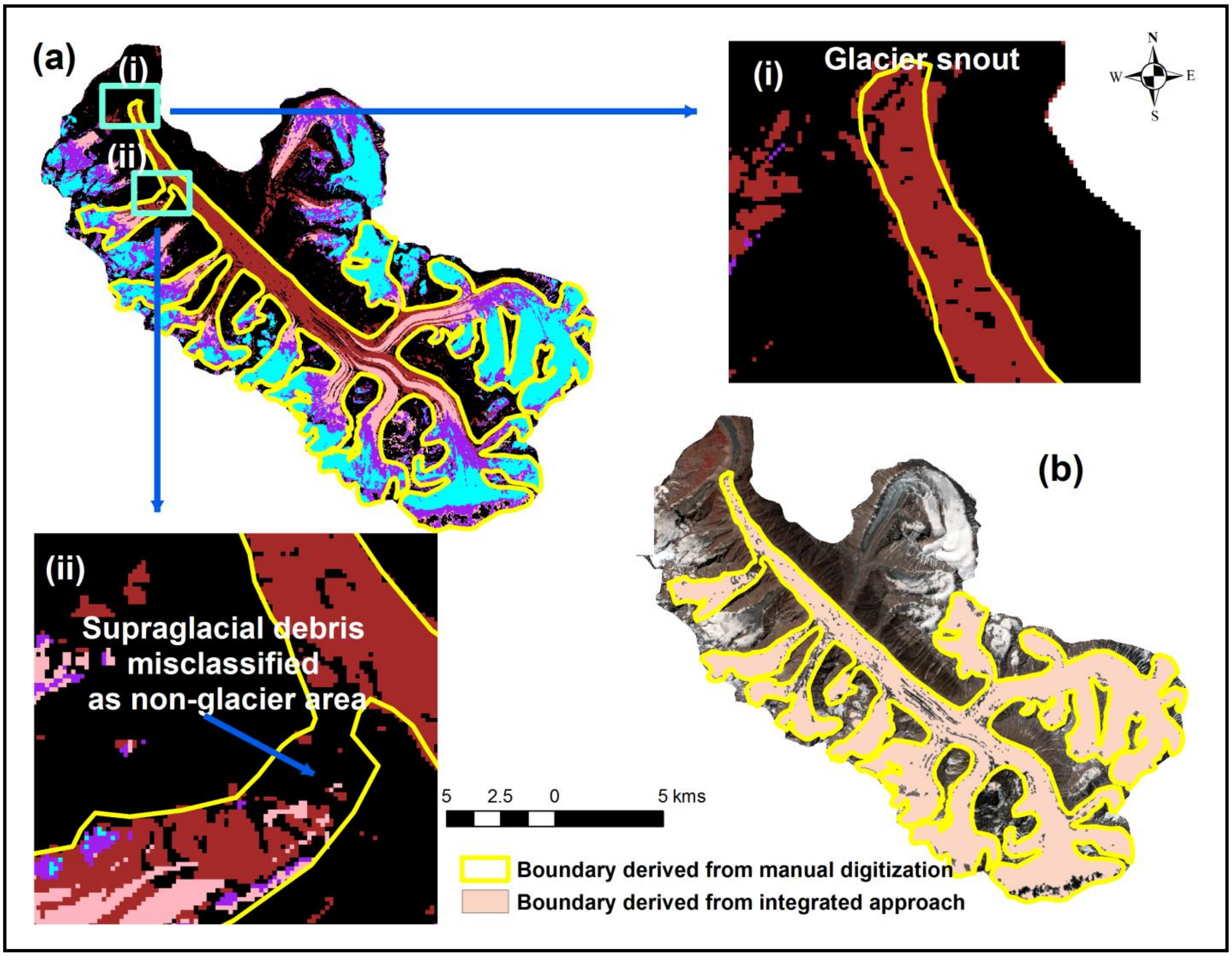

Figure 4, (a) Comparison of the boundary of Bara-Shigri glacier derived *(before neighbourhood analysis and manual editing)* from the integrated approach with the manually digitized boundary using high resolution LISS-IV image.

(i) Detailed view of the two boundaries showing proper demarcation of snout

(ii) Detailed view of the incorrect elimination of supraglacial debris from the classified output.

(b) Comparison of the final boundary*(in vector format)*of Bara-Shigri glacier derived *(after neighbourhood analysis and manual editing)* from the integrated approach with the manually digitized boundary using high resolution LISS-IV image.

boundary derived through the integrated approach, few pixels of supraglacial debris are misclassified as non-glacier area and the tributary glacier has been disconnected from the main glacier body (enlarged view of Fig. 4a (ii)). This misclassification took place as the slope value of this area are higher than the defined threshold value. Visual interpretation of LISS-IV image exhibits signatures of the development of crevasses, which is yet to be confirmed during the field visit. Therefore, the slope value of this part did not fit within the slope threshold used. Hence, a neighbourhood analysis and manual editing have been done on the classified map of the study area to remove all the regions that are not connected with the main glacier body of the Bara-shigri glacier. Thus, obtained final boundary of the glacier in vectorized form is overlaid and compared with the manually digitized boundary as shown in Fig. 4b. Detailed evaluation and visual comparison indicates that the boundary of Bara-Shigri glacier delineated using the integrated approach after some minor post-processing matches well with the manually delineated glacier boundary.

6. CONCLUSIONS

The present study attempts to systematically map the supraglacial covers of Bara-shigri glacier, an extensive debris-covered glaciers of western Himalaya. The proposed approach is faster in comparison to the manual delineation for delineating boundaries of debris-covered glaciers. The proposed approach combining all the rules using the benefits of spectral indices such as NDSI and SII, slope, elevation and thermal properties of different supraglacial covers enable us to accurately map the supraglacier debris covered glacier. The availability of SWIR bands in Landsat-OLI images helped to design snow-ice index which in turn helped to differentiate between snow and ice types, which is a challenging task through visual inspection. Along with slope and thermal information, elevation played an important role in demarcating supraglacial debris from non-glacier area. Although the integrated approach is proved suitable to map supraglacial covers of debris-covered glaciers, detailed filed investigation is needed for quantitative assessment of the obtained accuracy.

References

Berthier, E., Arnaud, Y., Kumar, R.,Ahmad, S.,Wagnon, P. and Chevallier,P. 2007. Remote sensing estimates of glacier mass balances in the Himachal Pradesh (Western Himalayas, India). Remote Sensing of Environment, 108 (3),pp. 327–338.

Bhambri, R., Bolch,T. and Chaujar,R.K. 2011. Mapping of debris-covered glaciers in the Garhwal Himalayas using ASTER DEMs and thermal data. International Journal of Remote Sensing, 32 (23),pp. 8095–8119.

Bolch, T., Buchroithner, M.F. Kunert, A. and Kamp,U. 2007. Automated delineation of debris-covered glaciers based on ASTER data. M.A. Gomarasca (Ed.), GeoInformation in Europe pp. 403–410. Millpress, Rotterdam, Netherlands.

Cogley, J.G. 2011. Present and future states of Himalaya and Karakoram glaciers. Annals of Glaciology 52 (59),pp. 69–73.

Ghosh, S., Pandey, A.C., Nathawat, M.S.,Bahuguna, I. M. and Ajai. 2014. Contrasting signals of glacier changes in Zanskar valley, Jammu & Kashmir, India using Remote Sensing and GIS. Journal of the Indian Society of Remote Sensing 42 (4),pp. 817-827.

Karimi, N., Farokhnia, A. Karimi, L. Eftekhari, M. and Ghalkhani,H. 2012. Combining optical and thermal remote sensing data for mapping debris-covered glaciers (Alamkouh Glaciers, Iran). Cold Regions Science and Technology 71,pp. 73–83.

Keshri, A.K., Shukla, A. and Gupta. R.P. 2009. ASTER ratio indices for supraglacial terrain mapping. International Journal of Remote Sensing30, 519–524.

Kulkarni, A. V., Bahuguna, I.M.,Rathore, B.P.,Singh, S.K.,Randhawa, S.S.,Sood, R.K. andDhar,S. 2007. Glacial Retreat in Himalaya using Indian Remote Sensing Satellite data. Current Science 92 (1),pp. 69–74.

Kulkarni, A.V., Rathore, B.P.,Mahajan, S. and Mathur,P. 2005. Alarming retreat of Parbati glacier, Beas basin, Himachal Pradesh. Current Science 88,pp. 1844–1849.

Mihalcea, C., Brock, B.W., Diolaiuti, G., Agata, C.D., Citterio, M., Kirkbride, M.P., Cutler, M.E.J. , Smiraglia, C. 2008. Using ASTER satellite and ground surface temperature measurements to derive supraglacial debris cover and thickness patterns on Miage Glacier (Mont Blanc Massif, Italy). Cold Region Science and Technology 52 (3), pp. 341–354.

Minora, U., Bocchiola, D.,D'Agata, C. D.,Maragno, D.,Mayer, C.,Lambrecht, A.,Mosconi, B.,Vuillermoz, E.,Senese, A.,Compostella, C.,SmiragliaC. and Diolaiuti,G. 2013. 2001–2010 glacier changes in the Central Karakoram National Park, a contribution to evaluate the magnitude and rate of the Karakoram anomaly. The Cryosphere Discussion 7,pp. 2891–2941.

Pandey, A.C., Ghosh, S. and Nathawat,M.S. 2011. Evaluating patterns of temporal glacier changes in Greater Himalayan Range, Jammu and Kashmir, India. Geocarto International 26 (4),pp. 321–338.

Paul, F., Huggel, C. and Kaab,A. 2004. Combining satellite multispectral image data and a digital elevation model for mapping debris-covered glaciers. Remote Sensing of Environment 89 (4),pp. 510–518.

Ranzi, R., Grossi, G.,IacovelliL. and Taschner. S. 2004. Use of multispectral ASTER images for mapping debris-covered glaciers within the GLIMS project. Proceedings of the International Geoscience and Remote Sensing Symposium (IGARSS 2004), 20–24, 1144–1147, Anchorage, Alaska, USA.Vol. 2. Piscataway, NJ, Institute of Electrical and Electronic Engineers.

Scherler, D., Bookhagen, B. and Strecker. M.R. 2011. Spatially variable response of Himalayan glaciers to climate change affected by debris cover. Nature Geoscience 4 (3), 156–159.

Shukla, A. and Ali,I. 2016. A hierarchical knowledge-based classification for glacier terrain mapping, a case study from Kolahoi Glacier, Kashmir Himalaya. Annals of Glaciology 57(71), pp. 1–10.

Shukla, A., Arora, M.K. and Gupta, R.P. 2010. Synergistic approach for mapping debris-covered glaciers using optical-thermal remote sensing data with inputs from geomorphometric parameters. Remote Sensing of Environment 114 (7),pp. 1378–1387.

Shukla, A., Gupta,R.P. and Arora,M.K. 2009. Instruments and methods, Estimation of debris cover and its temporal variation using optical satellite sensor data, a case study in Chenab basin, Himalaya. Journal of Glaciology 55 (191), 444–452.

Taschner, S., and Ranzi,R. 2002. Comparing opportunities of Landsat-TM and ASTER data for monitoring a debris-covered glacier in the Italian Alps within the GLIMS project. IEEE transactions on geoscience and remote sensing symposium 24–28.