© Society for Environment and Development, (India)
http://www.sedindia.in

Available online at www.sedindia.in/ewijst
ISSN: 0975-7112 (Print)
ISSN: 0975-7120 (Online)

Environ. We Int. J. Sci. Tech. 16 (2021) 41-52

Environment & We
An International
Journal of Science &
Technology

Approaches for Mapping Debris Covered Glaciers by Geospatial Techniques: A Review with Reference to Indian Himalaya

Shruti Dutta[1*], Rakesh K. Ranjan[2], Amit Prakash[3]
[1]Amity School of Earth & Environmental Sciences, Amity University Haryana, Gurugram, India
[2]Department of Geology, Sikkim University, Gangtok, India
[3*]Department of Environmental Science, Tezpur University, Sonitpur, Assam
*Email Id:shrutidutta2020@gmail.com

Article history:
Received 10 October 2020
Received in revised form
21 October 2020
Accepted 21 October 2020
Available online
10 April 2021

Keywords:
Debris covered glaciers;
Debris mapping;
Supra glacial debris;
Spectral indices;
Thermal remote sensing

Abstract

The debris cover on the glaciers has a profound role in the alteration of thermal regime of the glacier surface and influences the debris-glacier-climatic relationship. The multi-spectral and multi-temporal satellite images have become potentially invaluable tools for the mapping, regular monitoring and systematic assessment of the debris covered glaciers. However, similar spectral signatures of debris and adjacent bedrock become a limitation in its mapping. Since the conventional method of manual delineation on the satellite imageries is much time consuming and cumbersome, a number of methods using various algorithms and spectral indices have gradually evolved in the assessment of debris covered glaciers supplemented with field-based observations. The present work is an attempt to document various approaches and techniques used in the study of debris at the global level along with a focus on Indian Himalayan region. It also deals with the limitations and future challenges associated with these methods.

1. Introduction

Glaciers have gained significant interest and research momentum in the last few decades ever since they have been identified as potential water resources in the upstream region and its influence on the water supply downstream. The clusters of population settled in lowlands are highly dependent for their livelihood on these glacier systems as many important river systems have their origins in them. These river systems have an immense role to play in agricultural, industrial and drinking water demands as well as in hydropower generation (Kaser, *et al*., 2010; Vohra, 2010). Moreover, these glacier systems are also recognized as a major contributor in impacting the run-off downstream and subsequent recharge of river fed aquifers (Immerzeel, *et al*., 2010; Radic, *et al*., 2013). It is also a well perceived fact that the remoteness and the logistic constraints involved pose hindrance in regular monitoring and collection of data for these glaciers through conventional field methods. In such scenarios, remote sensing techniques involving multi-temporal and multispectral satellite images have become potentially invaluable tools for the mapping, regular monitoring and systematic assessment of these glaciers. Geospatial techniques become an effective tool to decipher minute relationships of glacier-topography-climate which in turn is the key to the response of surface processes and glacier dynamics.

The glaciated terrains have been found to have moderate to high levels of linkage with debris cover (Casey, *et al*., 2012). The debris covered glaciers (DCGs) pose a serious limitation in mapping of the glacier bodies because the spectral signature of both debris and the adjoining bedrock cannot be differentiated. Therefore, the accurate mapping and delineation of debris cover on glacier with the aid of identification of geomorphologic parameters becomes a challenging job and manual delineation of glacier boundaries was widely used to overcome this issue. Since this method was much time consuming and cumbersome, therefore numerous studies using various algorithms and spectral indices (Ghosh, *et al*., 2014) have gradually developed in the past to estimate and assess the glacier inventory and subsequent area-boundary status through remote sensing methods.

The origin of debris cover on a glacier comprises variable sources like local rock and ice falls or wind blown dust. The debris cover may also originate from volcanic eruptions, salts and microorganisms from sea spray, meteorites and pollutants (Benn, *et al*., 1998). However, the major process of debris generation on the glaciers is attributed to frost action (Benn, *et al*., 1998; Veettil, 2012). The supraglacial debris cover influences the melting of ice by acting as a blanket or insulating stratum. A thick debris cover acts like a blanket and insulates the incoming radiation whereas a thin debris cover may absorb higher radiation and reduce the albedo (Rounce, *et al*., 2014). Therefore, the ablation rate is accelerated for a glacier with a thin cover, usually less than a few centimetres whereas the rate is decelerated for a glacier with thicker debris cover (Nicholson, *et al*., 2018). This protective layer is capable of altering the glacier-climate response in comparison to a non-debris covered glacier, depending upon the thickness of debris on the glaciers (Jouvet, *et al*., 2011; Kirkbride, *et al*., 2013; Østrem, 1959; Pellicciotti, *et al*., 2014). Subsequently, a thickness beyond a critical level of 2cm (Østrem, 1959; Mattson, *et al*., 1993; Kayastha, *et al*., 2000) exhibits deceleration of ablation, also validated by field observations (Nakawo, *et al*., 1981; Conway, *et al*., 2000; Nicholson, *et al*., 2006; Reid, *et al*., 2010; Reid, *et al*., 2012). The debris-ablation dynamics is also closely governed by numerous other factors like lithological and textural aspects of the debris, moisture content, albedo and meteorological conditions and other causal factors like debris thickness, the thermal properties of the debris that control the melting pattern beneath the debris (Rounce, *et al*., 2014). A variation in spatial extent of debris is also dependent on the slope of the glacier, thus reflecting a progressive extension of debris behind the tongue of the glacier (Benn, *et al*., 2012) promoting concentrated ablation. Due to this variation in the melting, it paves the way for stagnation of the snout and development of supraglacial lakes (Rounce, *et al*., 2014).

The Himalayan region is now well established as the Third Pole, encompassing one of the massive cryospheric resources. A majority of Himalayan glacier (70-80 percent) are covered with debris and have been showing retreat since the Little Ice Age (Mayewski, *et al*., 1979; Sakai, *et al*., 2000; Dobhal, *et al*., 2013; Casey, *et al*., 2012). An observation of regional distribution across greater Himalaya reveals stagnant glaciers with stable fronts are rare (1.5 percent) in Western Himalaya and most common in Southern (28 percent), Northern (10 percent) and Hindu Kush (16 percent) Himalaya (Scherler, *et al*., 2011).The widespread debris on Indian Himalaya and its influence on the glacier ablation have profound intricate linkages with the differential fluctuation pattern affecting the micro climate of a region, forming an important constituent of the mountain valley system (Shukla, *et al*., 2016). Henceforth, it becomes imperative to have a qualitative and quantitative assessment of the glacial debris parameters like coverage, thickness and thermal properties so that the ablation rates can be modelled in real case scenario. The present article aims to document the advent of various techniques for mapping of debris cover and its gradual development with associated aspects. It is an attempt to elucidate the importance of debris cover and its variability in ablation pattern which has intimate linkages with glacier-climate interactions. This work presents a comprehensive review of mapping the areal extent and dynamics of DCGs and the limitations encountered.

2: The Evolution of Glacier-Debris Studies: A Global Perspective

The mapping and delineation of glaciers covered with debris using satellite imagery has gained much relevance throughout the world. The real challenge lies in the similarity of spectral responses of the debris cover and the adjacent terrain, compared to the glacier. Various methods/approaches have been devised and a number of studies have focused on advanced approaches for mapping DCGs to overcome this problem. The last two decades have been a milestone for a number of studies done on DCGs, and has witnessed a gradual evolution of multiple techniques and approaches.

2.1. Advancement in Mapping Debris Covered Glaciers

One of the pioneer studies for debris mapping was based on the identification of debris by its lower radiometric temperature signatures at Donjek glacier, St Elias Mt. Canada (Lougeay, 1974) because of the thermal contrast between glacial ice and buried ice. This study is a landmark since it brought in the concept of thermal remote sensing for the assessment of debris related phenomenon associated with the glaciers. This work was extended at Wrangell Mountain, Alaska (Lougeay, 1981) using the Thermal Infrared (TIR) image of Landsat 3. Another study of DCGs through the multispectral and geomorphometric digital terrain model (DTM) at Mt. Rainier, USA (Kieffer, 2000) revealed a distinct variation in curvature at glacier ice-lateral moraine boundary. This information was used to delineate the tongue of the glacier in combination with the central flow line. Thus, the glacier has been subdivided into different facies viz. debris-covered ice, terminal, medial moraine, exposed/snow covered ice.

Debris cover on Raikot and Siachen glacier, Karakoram Himalaya, has been studied (Shroder, *et al*., 2000) by using SPOT-PAN data and application of Artificial Neural Network (ANN) technique to estimate distinctive categories of debris load. A specific feedforward ANN was incorporated in view of multiple benefits over conventional algorithms application. This includes nominal training, generalizations, ability to ascertain non-linearity and uncertainty analysis (Hepner, *et al*., 1990), (Gong, 1996). Based on minimum selection of training sets, each ANN was trained for identification of five debris classes i.e., base glacier ice, shallow debris on white ice, moisture-laden shallow debris, thick debris-topographic high and thick debris-topographic low. The results have been validated by an empirical determination of ANN training parameters and structure along with accuracy assessment. The delineation of debris covers at Raikot glacier, Karakoram Himalaya, has been done using first and second order morphometric criteria, e.g., slope, aspect and profile-tangential curvature (Bishop, *et al*., 2001). An ISODATA cluster algorithm for application of the unsupervised classification was utilized, for cluster classification, and then the results were validated through field measurements, found to be in concurrence. The study suggests that a two-level hierarchical model precisely gave boundary for glaciers. However, a three-level hierarchical model has greater potential for diagnostic mapping capabilities and delineate debris cover. A multi-source approach was applied in the Swiss Alps using automated multispectral classification and DEM derived slope supplemented with neighbourhood analysis (Paul, *et al*., 2004). The change detection of DCGs was carried out and further validated using ASTER DEM showing satisfactory results. However, it did not give reasonable results by applying ANN classification of debris cover without DEM.Nevertheless, this method was a way ahead keeping in view the basic rules and wide applications of automated classification.

Landsat and TERRA-ASTER images were used to identify and delineate the partly DCGs called black glaciers (Ranzi, *et al*., 2004) at Belvedere and Miage Glaciers, Italian Alp based on the study of Lougeay (1974). The contrast in the surface temperature glacial ice and superimposed debris was observed to be approximately 4.5° C in this study. However, this study infers that sufficiently lower temperatures signatures apt for delineation of debris-covered glacier ice from surrounding terrain were found suitable only when thickness of debris cover did not exceed 40–50 cm. Thermal information and slope derived from ASTER (2001-03) was merged with an automated morphometric method (Buchroithner, *et al*., 2006) to map the DCGs in the Nepal Himalaya. This method was coupled with manual editing and elimination of unnatural peaks and voids in the elevation dataset. The results obtained give a good area estimate for glacier mapping having a variation of 2-5 percent from the manually mapped glaciers. It was suggested that a high spatial resolution of DEM can yield better results. The spatial and temporal change in supra glacial debris (SGD) of six glaciers (in vicinity of Adylsu valley, Central Caucasus Mountain, Russia) has been studied through manual delineation by using Landsat TM & ETM+ imagery (Stokes, *et al*., 2007). The areal extent of SGD of each glacier shows a variation in the range of 5-25 percent with an accelerated glacial retreat of 3 to 6 percent for the period 1985-2000. ASTER derived morphometric features and thermal information were compared with manual delineation to map the DCGs Khumbu Himal resulting in an area-deviation of approximately 5 percent (Bolch, *et al*., 2007). The outer and lateral part might not reflect indicators for mapping, especially in the areas of debris and areas where stagnant ice exists. However, this method can demarcate the glacier if the lateral moraines exist properly. A number of different methods i.e., manual, semi-automatic, modified semi-automatic, and automated approach have been applied to analyze the supra glacial debris (Veettil, 2012)at Baltoro glacier, Karakoram Himalaya. The thermal bands of Landsat TM and ETM + along with SRTM DEM have been used to map the DCGs. The manual approach gave a reasonable result, but is highly dependent on the skill of the user. However, the modified semi-automated method was found to be the most reliable approach, especially near the snout position and gave similar results compared to manual and automatic approaches.

Supra and periglacial debris have been identified and differentiated by using optical and thermal (Worldview-2 and Landsat-TM respectively) data supplemented by field observation and Neural Network classification on the heavily debris covered Alamkouh Glacier, Iran (Karimi, *et al*., 2012). The result thus obtained has been compared with the geo-morphometric and manual delineation techniques.The geomorphometric method was not found suitable for area extraction near the ablation and accumulation area because of considerable retreat and large amount of ice at slope respectively. However, the study suggests that the optical-thermal satellite data in combination with geo-morphometric-field approach is best suited to extract the debris covered glaciated area. The geochemical and mineralogical composition of the debris from Ngozumpa and Khumbu glaciers, Nepal Himalaya (Casey, *et al*., 2012) has been analysed and supraglacial mineral map was correlated with satellite thermal data to interpret the association of surface composition and surface temperature. This data can be used to improve and reduce probable errors that are linked with glacier debris radiative property, composition, areal extent and mass flux assessment. The mapping of distribution and thickness of supraglacial debris was attempted at Miage glacier (Foster, *et al*., 2012) by the thermal information from ASTER data using an energy balance model and subsequently validated by field observations. The land surface temperature (LST) of debris at various sites has been recorded through thermistor probes, meteorological data of ambient atmosphere has been measured from AWS and Debris thickness was estimated through digging the debris upto the ice. The model has been run to locate debris thickness in each pixel through the energy balance. This study was found to be suitable for a critical debris thickness up to 0.5m. The areas with larger debris might witness high uncertainty to find out thickness.

The thermal property of the material controlling the temporal behaviour of LST called thermal inertia (TI) has been applied to study ice debris landforms in the Mediterranean Andes (Brenning, *et al*., 2012). TI is a good response of a material to temperature changes and depends on bulk density, specific heat capacity and thermal conductivity of the material. Apparent thermal Inertia (ATI) which is a function of surface albedo, incoming solar radiation and maximum daily temperature difference has been calculated as a practical proxy for TI utilizing remotely-sensed data from ASTER G-DEM. The application of ATI mapping eliminates the topographic influences from the LST data, thereby showing a high potential of mapping in periglacial and glacial environments. Clean ice and debris were demarcated on the glaciers of Central Asia using semi-automated classification based on glacier velocity, topographic, spectral and spatial relationships between glacier areas and its surroundings (Smith, *et al*., 2015) with the help of Landsat 5 (TM), 7 (ETM+) and 8 (OLI). This rule-based algorithm is a robust and effective method across a diverse glaciated terrain, particularly with excessive debris cover where mapping of the glacier is not feasible. The study also suggests that this algorithm can be applied on a wide range of other glacial parameters like hypsometry, slope, aspect and also mass balance with consistent manual monitoring during the procedure. A temporal change estimation of SGD using Landsat (1977- 2014) images to assess the evolution of SGD in the Karakoram Himalaya was done considering separate observations for surge and non-surge glaciers (Sam, *et al*., 2015). The results show stable results, denoting almost zero alteration for both the types of glaciers. The debris cover has an intricate relationship with mass balance, gain in debris denoting loss in mass balance. This study on a regional level (93 glaciers) with zero change in debris cover connects to the Karakoram anomaly wherein stable fronts and mass balance have been observed in the region. Moreover, this study done for a time span of 37 years emphasizes that the stable regional mass front when integrated with stable debris cover might indicate an extended Karakoram anomaly than is presently reported.

A semi-automated debris cover mapping using the multi data approach (Landsat ETM+, Landsat TM and SRTM) in combination with thermal bands and DEM was carried out at Koxkar and Yengisogat glacier in China (Alifu, *et al*., 2015). This work introduces a distinct band ratio [band 6 TIR ÷ (band 4 VNIR ÷ band 5 SWIR)] to differentiate between periglacial and supraglacial debris and the result shows about 0.34 to 2% deviation from the

Randolph Glacier Inventory (RGI version 4.0) and Google Earth image. The 90 m spatial resolution of SRTM DEM turns out as a limitation which was rectified through manual editing. It has been suggested that an inclusion of morphometric parameters may give better output in terms of debris mapping on the glaciers. This work has further included the morphometric features (slope, plan, and profile curvature) with glacier terrain features for delineation of debris cover at Yengisogat glacier and found relatively better results (Alifu, *et al*., 2016). However, the spatial resolution of DEM still remains a limiting factor for this study as well. A spatio-temporal assessment of debris cover on the glaciers of Northern Patagonian Icefield was carried out through manual delineation with satellite imageries of Landsat TM, Landsat ETM+, Landsat OLI and ASTER GDEM for the period of 1987-2015 (Glasser, *et al*., 2016). The debris cover has been observed to increase by 3.8 percent and the change is correlated with glacier retreat, Snow line fluctuation, glacier velocity and emergence and growth of proglacial lakes.

The distribution of DCG based on the global dataset (RGI) excluding Greenland, Antarctica and Arctic (Sasaki, *et al*., 2016) has been carried out using the concept of thermal resistance with ASTER data (2009-2013) and validated with field measurements. The thermal resistance has been defined as the debris thickness divided by the thermal conductivity of the debris layer. About 16.8 percent of the area has been observed as DCGs, also witnessing the thickly covered debris to be about twice as compared to the thinly covered debris. This indicates a reduced/decelerated melting at the global scale. The database can be utilized into a global glacier model for evaluation of debris on glacial melting.

2.2. Measuring the Thickness of Debris

The debris thickness is another vital parameter to assess the glacial melt rate and supplements the inputs for hydrological models, evolution of glacial lakes and glacier-climate interactions in addition to debris mapping. Therefore, the estimation of thickness of glacier debris becomes of paramount importance in the study of glacier dynamics. The thickness of the debris has been correlated with land surface temperature at Miage Glacier, Mont Blanc Massif, Italy (Mihalcea, 2008a) and a debris thickness map has been prepared. *In situ* measurements using thermistors and ASTER derived surface temperature over consistent debris cover showed a strong correlation whereas it manifested a weak association on partially covered debris. The study uses surface temperature as an indicator of debris thickness; the former in turn shows a decreasing trend with an increase in elevation due to the upglacier decrease in surface energy receipts. Therefore, the role of elevation becomes critical in the assessment of debris thickness.The thermal resistance approach was applied along with meteorological data (AWS) through an energy balance model from Landsat 7 ETM+ (Rounce, *et al*., 2014) in order to assess the debris thickness in the Nepal Himalayan region. Non-linear temperature gradient model has been applied to derive the thickness of debris. The modeled thickness gives reasonable results, however, does not account for the fine local variations. The study incorporated a sensitivity analysis and reveals the importance of albedo and the effective thermal conductivity with respect to the debris cover parameters. Ground Penetrating radar (GPR) has been used to study the variability in the SGD thickness at Ngozumpa Glacier, Khumbu Himal, Nepal (Nicholson, *et al*., 2018). The study revealed a thick debris cover, highest towards the shallower slopes or on supraglacial ponds. It has also been reported that, sub-debris melt rate under thinner debris are expected to be significantly above average and even comparable with bare ice melt rate further upglacier. It has been suggested that large areas are susceptible to failure thus forming ablation hotspots (about 32%) associated with patches of thinner debris. A quantitative assessment of thickness of DCGs and its distribution has been carried out for Koxkar glacier, Tienshan Mountains (Huang, *et al*., 2018) and identified the factors controlling it. High resolution DEMs (SRTM-C 1S DEM, AW3D DEM, TanDEM-X) and high-resolution images (ALOS PRISM) coupled with field studies categorized the different zones viz. zone of minimal change (MT), zone of heavy thinning (HT) and zone of slight thinning (ST) and this differential ablation is attributed to the presence of ice cliffs and supraglacial lakes. Subsequently, the change in mass balance of DCG is nonlinear and highly complex. The thin debris, which otherwise shows higher ablation, does not exhibit thinning near the accumulation zone, whereas the presence of ice cliffs and supraglacial lakes enhance the thinning of thick debris covered areas. A comprehensive information of the approaches and methods used to study the DCGs has been summarized in the table 1.

Table 1: A tabular representation of the literature for study of debris covered glaciers at global level.

S. No	Work	Area of Study	Period of Study	Dataset	Approach
1.	Lougeay, 1974	Donjek glacier, St Elias Mt.,Canada	Not mentioned	Therma Infrared Sensors	Measurement of actual and radiant surface temperature
2.	Lougeay, 1981	Wrangell Mountain Alaska	1978	Landsat 3-Thermal Infrared Image	Manual Delineation, Unsupervised classification with thermal RS
3.	Kieffer *et al*. 2000	Mt. Rainer	1999	Landsat 7 and ASTER	Geomorphometric DEM analysis
4.	Shroder *et al*. 2000	Raikot, Shaigiri, and Sachen Glacier, Nanga Parbat Himalaya, Pakistan	Field work in 1984, 1993, 1995, 1996, and 1997, SPOT 1996	SPOT PAN Data, ANN	ANN
5.	Bishop *et al*. 2001	Raikot glacier, Nanga Parbat, Karakoram Himalaya	SPOT DEM 1996	SPOT Stereopair DEM	First and second-order morphometric
6.	Paul *et al*., 2004	Swiss Alps	1985 and 1998	Landsat TM (1985,1998) TM Bands 3,4,5 DEM 25 (Swiss topo2001) ASTER DEM	Automated multispectral classification along with DEM derived slope supplemented with neighborhood analysis and change detection
7.	Ranzi *et al*. 2004	Belvedere and Miage Glaciers, Italian Alps	2002	TERRA ASTER	Field measurements and energy balance modeling
8.	Buchroithner and Bolch, 2006).	Nepal Himalaya	2001-2003	ASTER DEM (2001-03) and thermal data	Automated morphometric method
9.	Stokes *et al*. 2007	Adylsu valley, Central Caucasus Mountain, Russia	1985-2000	Landsat TM (Band 3,4,5) & ETM+	Manual delineation by using FCCs validated by field observations
10.	Bolch *et al*. 2007	Khumbu Himal	2001-2003	ASTER DEM	Morphometric features and thermal information
11.	Mihalcea *et al*, 2007	Miage Glacier, Mont Blanc Massif, Italy	2005	ASTER	ASTER derived surface temperature compared with onsite measurements using thermistor
12.	Veettil, 2012	Baltoro glacier, Karakoram Himalaya	1990-2010	Landsat TM and ETM+ along with SRTM DEM	Various techniques including manual, semi-automatic, modified semi-automatic, and automatic method
13.	Karimi *et al*. 2012	Alamkouh glacier, Iran	2010	Worldview-2 and Landsat 5	Optical and thermal data been validated by field verification and supplemented by Neural Network classification.
14.	Casey *et al*, 2012	Ngozumpa and Khumbu glaciers, Nepal Himalaya	2009	Ngozumpa and Khumbu glaciers, Nepal Himalaya	Geochemistry and mineralogical composition of supraglacial mineral map, correlated with satellite thermal data

Continued table 1in next page……

Table 1 continued

S. No	Work	Area of Study	Period of Study	Dataset	Approach
15.	Foster *et al.*2012	Miage glacier	2005	Terra ASTER AST08 thermal bands	Thermal information from ASTER data using energy balance model and subsequently validated by field observations.
16.	Brenning *et al.* 2012.	Mediterranean Andes	2008	ASTER G-DEM.	Thermal inertia (TI) and remotely-sensed data from ASTER G-DEM.
17.	Rounce& Mc Kinney 2014	Everest region	2002-2008	Landsat7 ETM+ Meteorological data from AWS	Nonlinear energy balance model has been used to derive the thermal resistance
18.	Smith *et al.* 2015	Central Asia	1998-2013	Landsat 5 (TM), 7 (ETM+) 8 (OLI), SRTM	Semi-automated classification method based on velocity, topographic, spectral and spatial relationships between glacier areas and the surrounding environment, particularly with an excessive debris cover
19.	Sam *et al.* 2015.	Karakoram Himalaya	1977-2014	Landsat 8	Temporal change estimation of SGD considering separate observations for surge and non-surge glaciers
20.	Alifu *et al.* 2015	Koxkar and Yengisogat glacier in China	2009 Validated with 2013 field observation	Landsat ETM+, Landsat TM SRTM	A distinct band ratio [TIR ÷(VNIR÷SWIR)] to differentiate between periglacial and supraglacial debris
21.	Alifu *et al.*,2016	Yengisogat glacier	2009		Included the morphometric features (slope, plan, and profile curvature) with glacier terrain features
22.	Glassner *et al.* 2016	Northern Patagonian Icefield	1987-2015	Landsat TM Landsat ETM+, Landsat OLI ASTER GDEM	Manual delineation from satellite imageries
23.	Sasaki *et al.* 2016	Global Dataset excluding Greenland, Antractica and Arctic.	2009, 2013	RGI, 3A01 (ASTER)	Thermal resistance
24.	Nicholson *et al.*2018	Ngozumpa Glacier, Khumbu Himal, Nepal	2016	GPR, Pleiades DTM tri-stereo imagery	GPR survey and slope stability model
25	Huang *et al.* 2018	Koxkar glacier, Tienshan Mountains	2000,2009,2013	SRTM-C 1S DEM AW3D DEM TanDEM-X ALOS PRISM	High resolution DEM studies with field observation

3. Status of Debris covered glaciers in Indian Himalayan glaciers

The Indian Himalaya comprises a huge chunk of the Third Pole, characteristically controlled by factors like climate, topography, geometrical attributes and debris cover. The variation in the distribution of debris in Himalaya reflects a differential behavioral pattern of clean and DCGs and the response would further fluctuate with different levels of debris cover (Scherler, *et al*., 2011). A comprehensive understanding of the qualitative and quantitative status of debris cover, especially in Indian Himalaya is highly required to assess the debris-glacier-climatic inter-relation. Therefore, an application of appropriate techniques considering the debris covered nature of Himalaya which shows differential behaviour compared to global glaciated regime becomes a huge requirement, also to be extended at micro level in the Himalayan terrain.

3.1. Recent Studies on Mapping of Debris Covered Glacier

Supraglacial terrain was classified into four categories viz. snow, ice, ice-mixed-debris and debris using ASTER images at Chenab basin, Western Himalaya (Keshri, *et al*., 2009).The method considered three indices (i) Normalized Difference Snow Index (NDSI) (ii) Normalized Difference Glacier Index (NDGI) and (iii) Normalized Difference Snow Ice Index (NDSII) and their combination to differentiate and map the above mentioned four classes. The method was found to be suitable with 91% accuracy and the error was due to inability to differentiate between snow, ice, ice-mixed-debris and debris. The debris mapping through supervised classification of topographically corrected spectral reflectance data at Samudratapu glacier in Chenab basin (Shukla, *et al*., 2009) has been witnessed to be a favorable method using IRS-1C LISS-III (2001), IRS-P6 AWiFS (2004) along with Survey of India topographical maps (1963). Six land cover classes viz. snow, ice, mixed ice and debris, debris, valley rock, and water have been generated with an accuracy of 83.7 to 89.1 percent for mapping and 82 to 95 percent for individual class accuracy. The mapping of DCGs in Garhwal Himalaya (Gangotri, Chorabari, Raktavan, Chaturangi glacier (Bhambri, *et al*., 2011) through semi-automated methods involving multiple approach and morphometric analysis by using ASTER DEM (2004) and Landsat thermal data. The validation of ASTER DEM derived Gangotri glacier map shows a lesser area of 5.04 percent with respect to manually delineated map from Cartosat 1 and about 0.5 percent difference from IRS 1C PAN data.The mass movement derived depositions create noise and shadow area influence the single thermal band thresholding which ultimately pose limitations for semi-automated and automated mapping in the Himalayan terrain respectively. The spatial resolution of ASTER and thermal data hinders the semi-automated mapping of small glaciers with terminal moraines but holds good for large glaciers.

The heavily DCGs with low gradient snout have been observed to be stable (Scherler, *et al*., 2011) in comparison with the monsoon fed glaciers in comparison with the monsoon fed glaciers at Greater Himalaya (2000-2008) using remotely sensed data (ASTER and SPOT) for frontal change detection and surface velocities. The study highlights the absence of a consistent response of glaciers to climate change and its linkages with the debris cover to assess the glacier dynamics. Glaciated terrain of Tista Basin of Eastern Himalayahas been mapped (Basnett, *et al*., 2013) for the period of 1990-2010 through Landsat TM and IRS images and observed a loss of approximately 3.3 percent of the total glacier area, further witnessing evolution and expansion of supraglacial lakes on the DCGs which eventually merge with each other with time forming large lakes. The study reveals a faster rate of retreat for the DCGs as compared to the debris free glaciers. A multiple approach using optical and thermal remote sensing (Landsat TM/ETM+) along with ASTER-DEM derived morphometric parameters was utilized to derive semi-automated glacier outline of Hamtah and Patsio glaciers (Bhardwaj, *et al*., 2014). This method on Patsio glacier showed high correlation accuracy of around 91 percent and thereafter was replicated and verified for Hamtah glacier having a different geometry and terrain.The spatial resolution poses a limitation in the automated mapping of DCGs but the technique still gives a reasonable result and therefore can be applied for DCGs in Himalayan terrain. A multi-source approach for SGD classification using band ratio (TM-4/TM-5) image and Cartosat1-DEM derived slope was applied to map the six debris-covered glaciers in Ladakh region of Greater Himalaya (Ghosh, *et al*., 2014).Three classes viz. snow- and ice-covered parts of the glaciers, debris (supraglacial and periglacial) and surrounding non-glacierized areas (vegetation, valley rocks, water) have been categorised by using this approach. Supervised classification with principal component analysis was found to aid in recognition of snow and ice in Band 1, 2 and 3 of TM Image. The role of morphometric parameters integrated with band ratio is found to be a relatively efficient method for the analysis of SGD cover. A hierarchical knowledge-based classification (HKBC) distinguishes between supra and peri glacial debris using ASTER GDEM at Kolahoi Glacier, Kashmir Himalaya (Shukla, *et al*., 2016). The study applies the temperature difference to create a thermal mask and subsequently normalized difference debris index has been developed which is further validated with field observation. This approach was found to be more suitable and effective than maximum likelihood classification. The influence of differential debris cover (7-26 percent) on the glacier response was studied for five glaciers in the Zanskar region of Jammu & Kashmir,India (Shukla, *et al*., 2016) using ASTER GDEM (2009-2013). The lesser debris covered or clean glaciers (CG) witness higher retreat, deglaciation, Accumulation Area Ratio (AAR) and more peri and proglacial lakes as compared to the DCGs. The study highlights the influence of climatic factors in the variability of debris cover and glacier response in the same geographical region. A spatio-temporal change detection in SGD cover (1997-2014) using Landsat data was carried out in the Baspa basin, Western Himalaya (Pratibha, *et al*., 2018) using normalized difference snow index (NDSI) and band ratio of NIR and SWIR. The study showed a linear increase of 2.8 ± 0.4 percent in the debris cover validated through field observations with the existing literature (Kumar et. al. 2017; Kulkarni 2004) reflecting heavy debris cover for glaciers with smaller accumulation area ratio. A summary of the various approaches and methods used to study the DCGs in the Indian Himalayan region has been presented in Table 2

Table 2: A tabular representation of the literature for study of debris covered glaciers in Indian Himalayan region.

S. No	Work	Area of Study	Period of Study	Dataset	Approaches/Method
1.	(Keshri *et al*.2009	Chenab basin, Himalaya	2004	ASTER images	(i) Normalized Difference Snow Index (NDSI) (ii) Normalized Difference Glacier Index (NDGI) and (iii) Normalized Difference Snow Ice Index (NDSII) and their combination for debris classification
2.	Shukla *et al*., (2009)	Samudratapu glacier, Chenab basin	2001, 2004	IRS-1C LISS-III IRS-P6 AWiFS Survey of India topographical maps	Topographically corrected reflectance image data through supervised classification.
3.	Bhambri *et al*., (2011)	Gangotri, Chorababri, Raktavan, Chaturangi glacier/ Garhwal Himalaya	2004	ASTER DEM, Landsat ETM+, Cartosat-1, IRS 1C PAN data)	Semi-automated classification using morphometric parameters thermal data and validation with manually delineation
4.	Scheler *et al*., (2011).	Greater Himalaya	2000-2008	ASTER, SPOT, Landsat Thematic Mapper (TM) band TM4/TM5-ratio images	Sub-pixel cross-correlation band rationing (TM4/TM5).
5.	Kamp *et al*. (2011)	Parkachik and DrangDrung glaciers.	1975-2008	Landsat and ASTER	Morphometric features combined with thermal imagery and supervised classifiers supplemented with field measurements.
6.	Basnett *et al*., (2013)	Tista Basin of Eastern Himalaya	1990-2010	Landsat TM (Level 1T) and Indian Remote-sensing Satellite (IRS) LISS III, SoI Toposheets	False-colour composites along with DEM derived relief map and NDSI.
7.	Ghosh *et al*. (2014)	Greater Himalayan Range, Ladakh	2009	Landsat (TM4/TM5 band ratio), CartoDEM image	Morphometric attributes as well as band ratioing were used in combination with PCA and supervised classification
8.	Bhardwaj *et al*. (2014)	Hamtah&Patsio glacier.	1989-2011	Landsat TM/ETM + thermal band satellite data) ASTER GDEM	Semi-automated approach combining DEM derived morphometric parameters along with band ratioing and thermal data
9.	Shukla & Ali, 2016	Kolahoi Glacier, Kashmir Himalaya	2003	ASTER GDEM	A hierarchical knowledge-based classification (HKBC) using thermal mask and slope to develop normalized-difference debris index
10	Pratibha & Kulkarni 2018).	Baspa basin, Western Himalaya	1997-2014	Landsat	Normalized difference snow index (NDSI) and band ratio of near infrared and shortwave infrared

4. Conclusion

It has been extensively established that the debris cover on glaciers significantly alters the thermal regime of the surface, thus influencing the surface energy balance and glacier-climate dynamics. Henceforth, the debris cover reflects intricate linkages with climatic variability and can be affirmed as a sensitive indicator of glacier health. A considerable number of approaches and techniques to assess the qualitative and quantitative aspects of debris covered glaciers have been significant at the global level including Indian Himalaya. The onset of mapping DCGs through manual delineation gradually showed more efficiency using the thermal remote sensing and subsequently topographical and geomorphological attributes. It is evident that the studies on debris cover is based on manual delineation, multispectral classification, thermal-properties based methods, geo-morphometric analysis and a combination of these methods. The debris cover studies have been observed to be hindered by low spatial resolution and temporal data gaps of remote sensing data. The thickness of the debris also acts as a limiting factor for the assessment of the DCGs. Henceforth, a necessary field validation is highly recommended for all the techniques. The gradual evolution of various methods and techniques also reflect that the efficiency of these methods is dependent on geographical and climatic regimes, thus applying an appropriate methodology. A large number of prospective techniques and methods can be explored ahead and can be integrated with the existing literature/previous studies. A potential challenge is the analysis of remote sensing data in DCGs and to model its response to changing climate scenarios. The response of debris exhibits a spatial and temporal variability and the nuances needs to be looked and further explored into.

Author's contribution: *Shruti Dutta (Assistant Professor) wrote Conceptualization, Methodology, Writing- Original draft preparation and also corresponding author, Rakesh K. Ranjan (Assistant Professor) did Conceptualization of manuscript, Amit Prakash (Assistant Professor) done Writing- Reviewing and final Editing*

Acknowledgements: *Shruti Dutta would like to acknowledge Amity University, Haryana for encouragement and support. Rakesh K. Ranjan extends acknowledgement to DST's CoE on Water Resources, Cryosphere and Climate Change Studies at Sikkim University, Gangtok for motivation.*

Conflict of Interest: The authors declare that there is no conflict of interest.

References:

Alifu, H., Johnson, B. A., Tateishi, R. 2015, A new band ratio technique for mapping debris-covered glaciers using Landsat imagery and a digital elevation mode. *International Journal of Remote Sensing, 36:8*, 2063-2075.

Alifu, H., Johnson, B. A., Tateishi, R. 2016, Delineation of Debris-Covered Glaciers Based on a Combination of Geomorphometric Parameters and a TIR/NIR/SWIR Band Ratio. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 9 (2), 781-792.

Basnett, S., Kulkarni, A. V., Bolch, T. 2013, The Influence of Debris Cover and Glacial Lakes on the Recession of Glaciers in Sikkim Himalaya, India. *Journal of Glaciology , 59* (218), 1035–1046.

Benn, D. I., Evans, D. J. 1998, Glaciers and Glaciation. New York: Arnold.

Benn, D. I., Bolch, T., Hands, K., Gulley, J., Luckman, A., Nicholson, L. I., Quincey, D., Thompson, S., Toumi, R., Wiseman, S. 2012, Response of Debris-Covered Glaciers in the Mount Everest Region to Recent Warming, and Implications for Outburst Flood Hazards. *Earth-Science Reviews*, 114 (1–2), 156–174.

Bhambri, R., Bolch, T., 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), 8095-8119 .

Bhardwaj, A., Joshi, P. K., Snehmani, Singh, M. K., Sam, L., Gupta, R. D. 2014, Mapping debris-covered glaciers and identifying factors affecting the accuracy. *Cold Regions Science and Technology* (106–107), 161-174.

Bishop, M. P., Bonk,R., Kamp,U, J., Shroder, J, F. 2001, Terrain analysis and data modeling for alpine glacier mapping. *Polar Geography*, 25(3), 182–201.

Bolch, T., Buchroithner, M. F., Kunert, A., Kamp, U. 2007. Automated delineation of debris covered glaciers based on ASTER data. *Proceeding of the 27th EARSeL-Symposium,* (pp. 403–410). Millpress, Netherlands.

Brenning, A., Pena, M. A., Long, S. 2012, Thermal remote sensing of ice-debris landforms using ASTER: an example from the Chilean Andes. *The Cryosphere*, 6, 367–382.

Buchroithner, M.F., Bolch, T. 2007. An Automated Method to Delineate the Ice Extension ofthe Debris-Covered Glaciers at Mt. Everest Based on ASTER Imagery. *Proceedings of the 9th International Symposium on High Mountain Remote Sensing Cartography*, 14–22 September 2006 held inGraz, Austria, 8 pp.

Casey, K. A., Kaab, A., Benn, D. I. 2012, Geochemical characterization of supraglacial debris via in situ and optical remote sensing methods: a case study in Khumbu Himalaya, Nepal. *The Cryosphere*, Vol 6 No 1, 85—100.

Conway, H., Rasmussen, L. A. 2000,. Summer temperature profiles within supraglacial debris on Khumbu Glacier, Nepal. IAHS PUBLICATION. Debris Covered Glaciers .

Dobhal, D. P., Mehta, M., D, S. 2013, Influence of debris cover on terminus retreat and mass changes of Chorabari Glacier, Garhwal region, central Himalaya, India. *Journal of Glaciology*, 59, 961–71.

Foster, L. A., B. B., Cutler, M. E., Diotri, F. 2012, A physically based method for estimating supraglacial debris thickness from thermal band remote-sensing data. *Journal of Glaciology,* 58, 677–691.

Ghosh, S., Pandey, A. C., Nathawat, M. S. 2014, Mapping of debris covered glaciers in parts of the Greater Himalaya Range, Ladakh, western Himalaya, using remote sensing and GIS. . *Journal of Applied Remote Sensing*, *8(1) 083579*, 1-17.

Glasser, N. F., Thomas, H. O., Evans, Z. D., Davies, B. J., Mauri, P., Harrison, S. 2016, Recent spatial and tem poral variations in debris cover on Patagonian glaciers. *Geomorphology*, doi: 10.1016/j.geomorph.2016.07.03

Gong, P. A. 1996, Mapping, ecological land systems and classification uncertainties from digital elevation and forest-cover data using neural networks. *Photogrammetric Engineering and Remote Sensing*, 62 (11), 1249-1260 .

Hepner, G. F., Logan, T., Ritter, N., Bryant, N. 1990, Artificial neural network classification using a minimal trainingset: comparison to conventional supervised classification. *Photogramnmetric Engineering and Remote Sensing*, 56, 469-473.

Huang, L., Li, Z., Han, H., Tian, B., Zhou, J. 2018, Analysis of thickness changes and the associated driving factors on a debris-covered glacier in the Tienshan Mountain. *Remote Sensing of Environment*, 206, 63-71.

Immerzeel, W. W., Van Beek, L. P., Bierkens, M. F. 2010, Climate change will affect the Asian water towers. *Science*, 328, 1382–1385.

Jouvet, G., Huss, M., Funk, M., Blatter, H. 2011, Modelling the retreat of Grosser Aletschgletscher, Switzerland, in a changing climate. *Journal of Glaciology* 57, 1033–1045.

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

Kaser, G., Großhauser, M., Marzeion, B. 2010, Contribution Potential of Glaciers to Water Availability in Different Climate Regimes. *Proceedings of the National Academy of Sciences*, 107, pp. 20223–20227.

Kayastha, R. B., Takeuchi, Y., Nakawo, M., Ageta, Y. 2000, Practical prediction of ice melting beneath various thickness of debris cover on Khumbu Glacier, Nepal, using a positive degree-day factor. IAHS-AISH.264, pp. 71-81. IAHS-AISH P.

Keshri, A. K., Shukla,A, Gupta, R.P. 2009, ASTER ratio indices for supraglacial terrain mapping. *International Journal of Remote Sensing, 30* (2), 519-524.

Kieffer, H. 2000, New eyes in the sky measure glaciers and ice sheets. *EOS,* Transactions, *American Geophysical Union*, 81(24), 265,270, 271.

Kirkbride, M. P., Deline, P. 2013, The formation of supraglacial debris covers by primary dispersal from transverse englacial debris bands. *Earth Surface Processes and Landforms,* 1779–1792.

Lougeay, R. 1981, Potentials of Mapping Buried Glacier Ice with LANDSAT Thermal Imagery: In Satellite Hydrology, American Water Resources Association, *Proceedings of the 5th Annual Pecora Symposium,*Sioux Falls, South Dakota (pp. 189-192).

Lougeay, R. 1974, Detection of buried glacial and ground ice with thermal infrared remote sensing. *In Advanced concepts and techniques in the study of snow and ice resources,* Washington, DC: In H. S. Santeford, & J. L. Smith (Eds.) pp. 487–494.

Mattson, L. E., Gardner, J. S., Young, G. J. 1993, Ablation on Debris Covered Glaciers: an Example from the Rakhiot Glacier, Punjab, Himalaya. *In Snow and Glacier Hydrology* (eds Young, G.J.) (pp. 289-296). IAHS Publ. 218, Wallingford.

Mayewski, P. A., Jeschke, P. 1979, Himalayan and Trans-Himalayan Glacier Fluctuations Since AD 1812. *Arctic and Alpine Research, 3* (11), 267-287.

Mihalcea, C. B. 2008a, Using ASTER satellite and ground-based surface temperature measurements to derive supraglacial debris cover and thickness patterns on Miage Glacier (Mont Blanc Massif, Italy), 52, 341–354, 2008a *Cold Regions Science and Technology, 52*, 341–354.

Nakawo, M., Young, G. J. 1981, Field Experiments to Determine the Effect of a Debris Layer on Ablation of Glacier Ice. *Annals of Glaciology*, 2, 85-91.

Nicholson, L. I., Benn, D. 2006, Calculating ice melt beneath a debris layer using meteorological data. *Journal of Glaciology*, 52, 463–70.

Nicholson, L., McCarthy, M., Pritchard, H., Willis, I. 2018, Supraglacial debris thickness variability: Impact on ablation and relation to terrain properties. *The Cryosphere*, 12, 3719–3734.

Østrem, G. 1959, Ice melting under a thin layer of moraine, and the existence of ice cores in moraine ridges. *Geografiska Annaler*., 41, 228-230.

Paul, F., Huggel, C., Kääb, A. 2004, Combining satellite multispectral image data and a digital elevation model for mapping debris-covered glaciers. *Remote Sensing of Environment*, 89, 510-518.

Pellicciotti, F. S., Miles, E., Immerzeel, W. W., Bolch, T. 2014, Mass balance changes of the debris-covered glaciers in the Langtang Himal in Nepal between 1974 and 1999, *Journal of Geophysical Research*, 61, 373–386.

Pratibha, S., Kulkarni, A. V. 2018, Decadal change in supraglacial debris cover in Baspa basin, Western Himalaya . *Current Science*, 114 (4), 792-799.

Radic, V., Bliss, A., Beedlow, A. C., Hock, R., Miles, E., Cogley, J. G. 2013, Regional and global projections of twenty-first century glacier mass changes in response to climate scenarios from global climate models. *Climate Dynamics*, 42, 37–58.

Ranzi, R., Grossi, G., Iacovelli, L., 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 Sympogium*, Institute of Electrical and Electronic Engineers, Piscatawa. pp. 1144–1147.

Reid, T. D., Brock, B. W. 2010, An energy-balance model for debriscovered glaciers including heat conduction through the debris layer. *Journal of Glaciology*, *56*, 903–916.

Reid, T. D., Carenzo, M., Pellicciotti, F., Brock, B. W. 2012, Including debris cover effects in a distributed model of glacier ablation. *Journal of Geophysical Research,* 117, D18105,.

Rounce, D. R., McKinney, D. C. 2014, Debris thickness of glaciers in the Everest area (Nepal Himalaya) derived from satellite imagery using a nonlinear energy balance model. *The Cryosphere*, 8, 1317–1329.

Sakai, A., N, T., Fujita, K., Nakawo, M. 2000, Role of supraglacial ponds in the ablation process of a debris-covered glacier in the Nepal Himalayas. *IAHS Publ. 264* (pp. 119–130). *Symposium at Seattle 2000 – Debris-Covered Glaciers*.

Sam, H., Pellicciotti, F., Alvaro, A., Anna, C., Christian, K., Joseph, S., Shrestha A. 2015. Satellite observations show no net change in the percentage of supraglacial debris-covered area in northern Pakistan from 1977 to 2014. *Journal of Glaciology*, Vol. 61, No. 227, 2015 , 61 (227).

Sasaki, O., Noguchi, O., Zhang, Y., Hirabayashi, Y., Kanae, S. 2016, A global high-resolution map of debris on glaciers derived from multitemporal ASTER images. *The Cryosphere Discuss*, doi:10.5194/tc-2016-222, 2016

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

Shroder, J. F., Bishop, M. P., Copland, L., Sloan, V. F. 2000, *Debris-covered glaciers and rock glaciers in the Nanga Parbat Himalaya*, Pakistan. *82*, 17-31.

Shukla, A., 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), 1-10.

Shukla, A., Qadir, J. 2016, *Differential response of glaciers with varying debris cover extent: evidence from changing glacier parameters*. 37:11, 2453-2479.

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

Smith, T., Bookhagen, B., Cannon, F. 2015, Improving semi-automated glacier mapping with a multi-method approach: applications in central Asia. *Cryosphere,* 9 (5), 1747-1759.

Stokes, C. R., Popovnin, V., Aleynikov, A., Gurney, S. D., Shahgedanova, M. 2007, Recent glacier retreat in the Caucasus Mountains, Russia, and associated increase in supraglacial debris cover and supra-/proglacial lake development. *Annals of Glaciology*, 46, 195–203.

Veettil, B. K. 2012, A remote sensing approach for monitoring debris-covered glaciers in the high altitude Karakoram Himalayas. *International Journal of Geomatics and Geosciences,* 2(3), 833–841.

Vohra, C. P. 2010, *Glaciers of India—A Brief Overview of the State of Glaciers in the Indian Himalaya in the 1970s and at the End of the 20th Century.* In *Satellite Image Atlas of Glaciers.*