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GIS-BASED STUDY OF CRYOSPHERE, WATER AND LULC PATTERN IN THE WATERSHED OF KHANGRI GLACIER, ARUNACHAL PRADESH

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ABSTRACT

Himalayas are the source of water to many important snow/glacier-fed and rain-fed rivers in India and its neighbouring countries that caters the demand of water to more than 1.4 billion people. However, Himalayan glaciers are under threat due to impact of climate change and resulted in increasing in glacier retreating rates in recent decades. Moreover, with the retreating glaciers, nearby LULC pattern such as total snow cover area, vegetation line, barren land, etc. also changes. Therefore, it is imperative to study the glacier to address the impacts of climate change. But glacier studies are rare owing to difficult terrain, extreme climatic events and limited infrastructure. Therefore, use of Remote Sensing (RS) are most sought of due to its sustainability and repetitive ground coverage. In present study, RS based datasets were used in Khangri glacier and computation were performed for deriving glacier mass balance, snow cover area mapping, snout monitoring, snowline identification, velocity profile and LULC classification of the watershed. The study also gives the insight of application of Snap tool for the estimation of glacier velocity using the temporal Sentinel 1 Synthetic Aperture Radar (SAR) data. Moreover, the paper discusses the techniques to interpret the field based observations over the GIS platform in easy manner. Additionally, using the field based observation the RS based findings were validated on ground, geo co-ordinates of snout of the glacier were acquired for years 2017, 2018 and 2019, the emerging streams from the snout of the glacier was studied for its water discharge estimation. Study shows the stable trend of snout location but negative mass balance from year 2000 to 2008 as derived from RS based observations. These initial observations and or estimation need to be continued in future to arrive at any specific conclusions with respect to impacts of climate change on glacier health of Khangri glacier so that corresponding policy inputs can be given to the concern stakeholders.

***Keywords**: Glaciers, Mass balance, LULC pattern, Discharge, Water Quality, RS, GIS.*

INTRODUCTION

Himalayas are known for snow-fed rivers and streams that drain the region and supply the water not only to humans but also act as the lifeline to the flora and fauna of the region. These rivers carry water with them in the form of either snowmelt, glacier melt or rain water. Glacier which is a vast body of ice mass that moves over landmass due to its own weight and slope of the underlying topography is directly affected by climate change (Bisht, 2015). Therefore, glaciers are considered as an important indicator of climate change and therefore its monitoring is recognized as an important subject of interest to researchers (Khalsa *et al.,* 2004). Among the studies, accurate assessment of glacier mass and snow cover mapping is important in understanding the glaciers dynamics. However, traditional methods to study glaciers are cumbersome, time consuming and observations were also affected by terrain conditions or accessibilities. Recent advances in satellite remote sensing allow gathering information of an object on the ground without having physical contact. Advanced sensor technology provides repetitive coverage of glaciers and therefore is useful in monitoring the glacier in easiest way. Majority of recent studies are RS based glacier monitoring studies which revolutionized the way we are monitoring the glaciers. The glaciers of the greater Himalayas are located at an altitude of more than 5000 m where the extreme condition makes accessibility very difficult. However, with the availability of Remote Sensing data products in the visible, infrared, thermal and microwave regions have created new opportunities to study and monitor the glaciers located in far-flung high altitude regions. The satellite imageries provide the earth's surface data at a resolution of better than 30 cm. The freely available datasets of Sentinel and ALOS Palsar provides the data of earth surface at a resolution of 5 * 20 m at interferometric wide swath (IW) mode and Digital Elevation Model (DEM) data at 12.5 m resolution (https://sentinel.esa.int/web/sentinel/user-guides/sentinel-1-sar/acquisition-modes/interferometric-wide-swath).

Study on Himalayan glaciers shows that most of the glaciers are retreating with few exception where they are advancing or static. Few examples such as the Dudh Koshi are retreating at rates ranging from 10 to 60 m per annum, and many glaciers smaller than 0.2 km^2 have already disappeared (Bajracharya *et al.,* 2007). The increase in global temperature, an increase in extreme events of precipitation lead to diminishing streams of lower order or otherwise flash floods in the Himalayan region (Joshi & Kumar 2006). During last century, Himalayan glaciers observed varied retreat rate attributed to global warming (Bhambri and Bolch, 2009; Prasad *et al.,* 2009). Gangotri, one of the main glacier in Central Himalaya reported an average retreat rate of 5.9±4.2 m $year^{-1}$ during 1965 to 1968 and 26.9±1.8m $year^{-1}$ from 1968 to 1980. Further it retreated 21.0±1.2m $year^{-1}$ during 1980 and 2000 and retreat rate of Gangotri has declined to 7.0±4.0 m $year^{-1}$ during 2001-2006 (Bhambri *et al.* 2012). In context to Indian Himalaya, only a

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few glaciers being studied and monitored on a regular basis (Kasturirangan *et al.,* 2013).

Remote sensing techniques and its derived products have been used to track glacier geometry (Khalsa et al., 2004), to monitor velocity of different glacier and then to determines ice discharge (Scherler et al., 2008), glacier lake study (Gardelle et al., 2011), morphometric characteristics of glacier in Indian Himalayas (Ahmad et al., 2004) etc.

Studies on glaciers systems are available for a long time but concentrated on major or big glaciers. The small glaciers system is neglected somehow in shadow on big glacier system. Further, in-situ field verification is also lacking in some RS based studies. Therefore, it is important to understand the dynamism involved in small glacier system and its associated LULC changes if any and to verify the glaciers status using field observation. The study aims to finds the dynamics of small glacier using freely available remote sensing products for estimation of mass balance, snout monitoring, velocity measurement, snow cover area (SCA) mapping and snowline delineation, LULC pattern and also the study of water discharge. Present study was carried out in Khangri glacier (locally also known as Patliputra glacier) located at an altitude of approximately 4900 m above MSL in Tawang district of Arunachal Pradesh.

MATERIALS AND METHODS

Study area and Data used

Khangri glacier watershedlies between 27°46'57"N to 27°48'45"N latitudes and 92°21'16"E to 92°23'17"E longitudes and covers an area of approximately 178 km^2 (Fig. 1). The watershed of the glacier has been taken as the

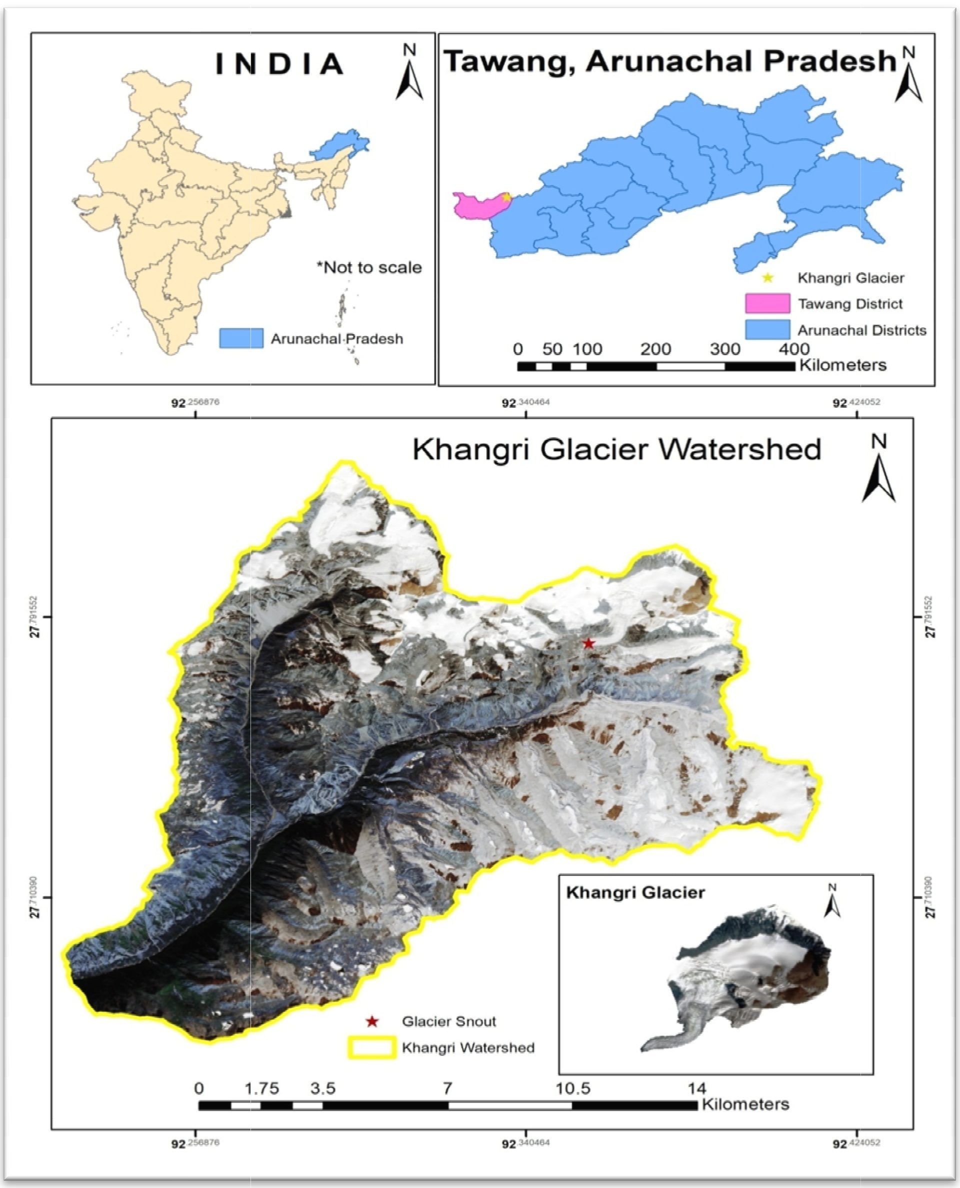


Fig. 1 Study area map of Khangri glacier and its watershed ***(Source: Sentinel 2B)***

area of interest for the study. It is located in the eastern Himalayan cryosphere near Gori Chain Mountain and its accumulation region lies on as high as 6300 m elevation in Tawang district, Arunachal Pradesh. This glacier is the major source of fresh water for the downstream region. The mountain is covered by meadows and alpine shrubs at higher elevations.

The freely available datasets of Sentinel 1 SAR microwave remote sensing data and Advance Land Observing Satellite (ALOS) - Phased Array type L-band Synthetic Aperture Radar (PALSAR) that provides the data of earth surface at a resolution of 5m*20 m and Digital Elevation Model (DEM) data at 12.5 m resolution respectively has been used for the study. The data were directly downloaded from https://search.asf.alaska.edu/#/.

METHODOLOGY

The data has been acquired through field surveys as well as using the remote sensing data products. During field visits, the results of remote sensing data products such as Land Use Land Cover (LULC) patterns were also verified using the DGPS survey. DGPS survey can give the accuracy of sub centimetre based on the accurate calibration of the reference station. Using the DGPS reference station geo-coordinates of snout were acquired for different years and were plotted on a GIS platform to study the change of snout position in order to understand the retreating or advancing trend of glacier. Moreover, during the in-situ survey, the water discharge of the Khangri stream was calculated at a suitable location using the cross-section and velocity method.

A brief methodology is presented in the flowchart shown in Fig. 2. Satellite imagery provides the surface feature distribution pattern whereas the DEM data is used to understand the topography of the terrain. After the necessary co-registration, projection and pre-processing of the satellite datasets, the image is required to be classified using the GIS methods of classification. Pixel Based Classification (PCB) technique of Unsupervised Based Classification (USBC) and Segmentation Based Classification (SBC) which is also known as object based classification methods were used to classify the imagery to derive the land cover pattern (LCP) of the area. Under Segmentation based Classification Approach (SCA), Normalised Difference Snow Index (NDSI) was used to directly derive the snow cover area from the satellite imagery based on the threshold value which varies for different glacier and for the Khangri glacier it was found

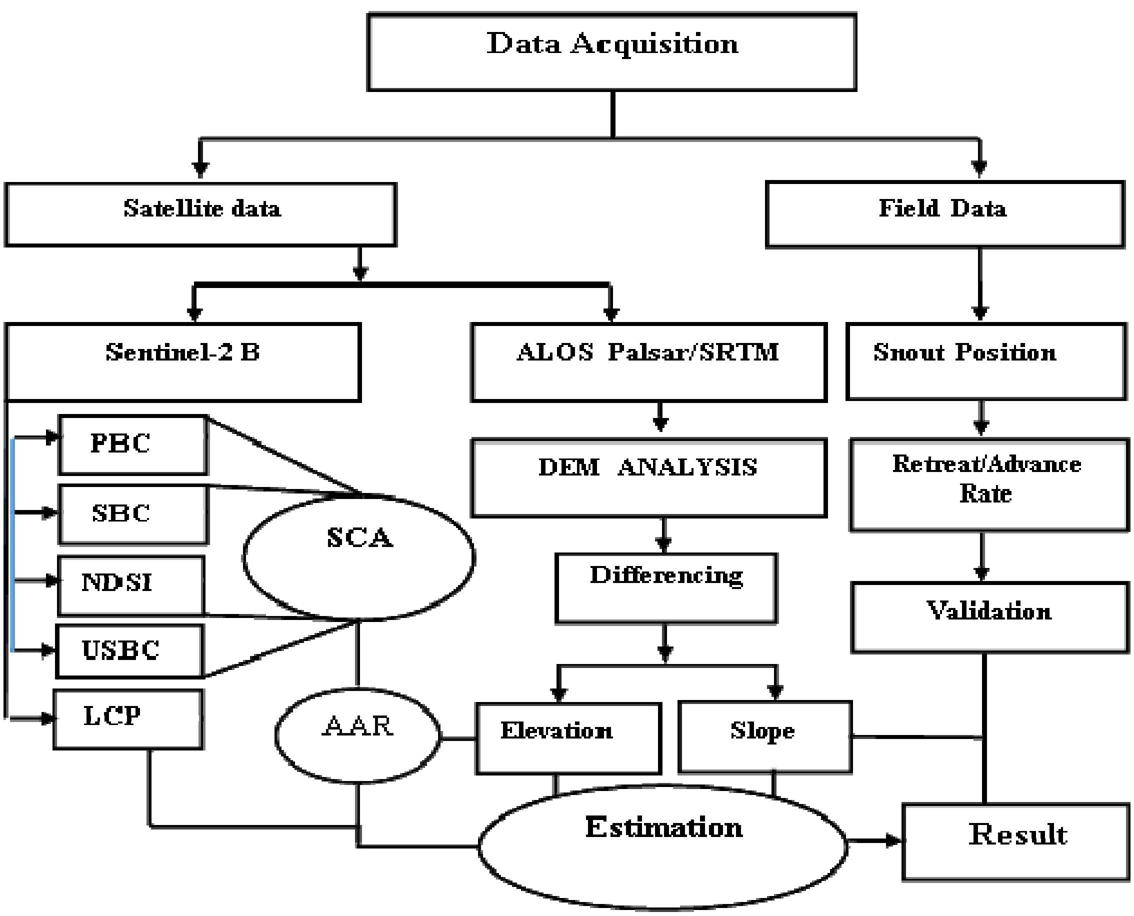


Fig. 2 Flowchart of methodology adopted in present study

out to be more than 0.87. The results of unsupervised classification and segment based classification were checked for accuracy. The result of segment based classification was found out to be more promising having the accuracy of more than 90%. The snow cover area was calculated and also the Accumulation Area Ratio (AAR) is calculated using the standard formula:

(AAR = Snow cover area / Total area of the glacier)

Mass balance of the glacier can be derived using the geodetic methods, using the AAR, DEM differencing methods, etc. For our study, the DEM differencing method was adopted using the ALOS PALSAR DEM data of year 2008 and SRTM DEM data of year 2000 for the known area of the Khangri glacier. The difference in value gives the loss/gain in mass of the glacier.

The watershed of the Khangri glacier was delineated over the GIS platform. The natural colour composite was prepared using Sentinel 2B satellite data at 10 m data with band 2 (Blue), 3 (Green), 4 (Red), 8 (near-infrared) and 11 (short wave infrared). Pre-processing such as radiometric and geometric correction was incorporated carefully. For projection UTM WGS 1984 46N was used to carry out the mathematical operations such as area calculations.

RESULTS AND DISCUSSION

Snout Monitoring

The terminus of the glacier in the ablation zone is termed as snout and the melting ice yields a stream of water. During ablation season, the snout of the glacier retreats and reaches a maximum point termed as Equilibrium line after which there is no further retreat. Therefore, the monitoring of snout is very important in order to assess the net mass balance at the end of the ablation season.

The study on the Khangri glacier has been initiated in 2017 only and studied for the location of its snout in 2017, 2018 and 2019 using the DGPS on-ground survey. It was observed that between 2017 and 2018 there was a lesser variation of the location of snout which was found to be more between 2018 and 2019 (Fig. 3). The reason of higher recede between the year 2018 and 2019 could be attributed to the fact that the data collection in 2019 was carried out at the end of ablation season when the snout of the glacier recedes to its maximum value and for year 2018, the observation was carried out in mid of ablation season. This is first ever observation in the Khangri glacier and more such observation is needed to establish the observed fact.

Velocity Assessment

The accumulation zone of the glacier receives the precipitation in the form of snow. Successive snowfall stratifies the snow layers under the weight of above

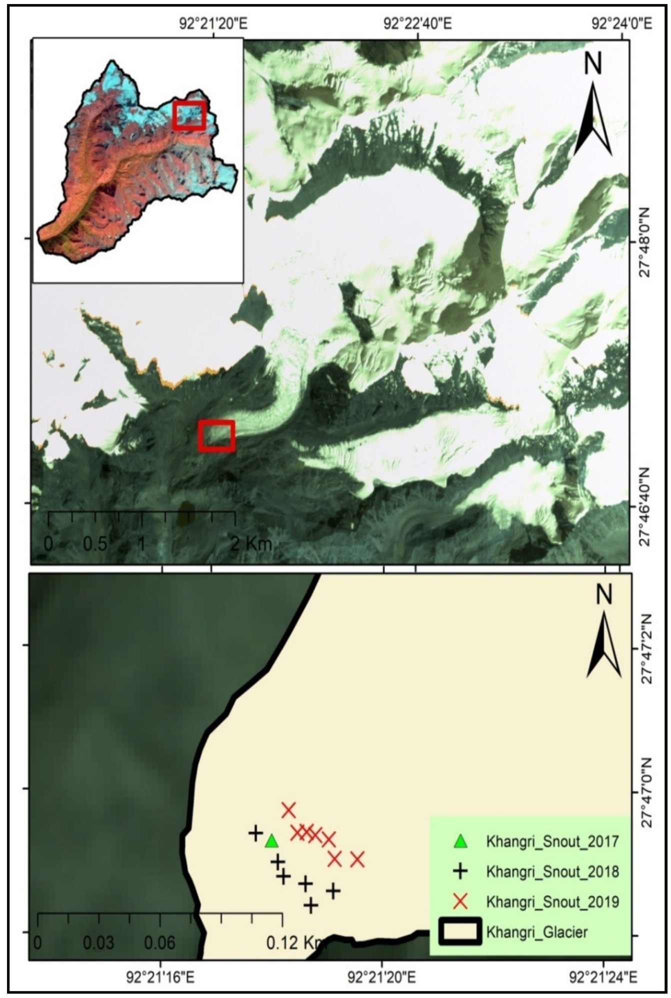


Fig. 3 Snout Monitoring of Khangri Glacier in 2017, 2018 and 2019

successive layers compressed to ice. The mass of ice under the impact of gravity moves down and reaches the ablation zone. The more is the mass of ice, the more will be the velocity. The velocity is therefore, a very important feature of the glacier which is required to be studied in order to understand the rate of downward displacement along with the direction (Jawak et. al 2018).

The study of velocity measurement was carried out through the installation of stakes on the ground and also using the freely available microwave remote sensing data products such as Sentinel 1 SAR data at 5m * 20m resolution. European Space Agency (ESA) provides a free tool known asthe Sentinel Application Platform (SNAP) for the assessment of glacier velocity using the microwave remote sensing and topography data (https://step.esa.int/main/toolboxes/snap/).

SNAP tool was used to determine the velocity of Kahngri Glacier between 19 August – 24 September, 2019 using the Sentinel 1 data. It was observed that the velocity in the main glacier boundary varies between 0.0045 m/day to 1.295

m/day. The profile graph was plotted from the location of the snout to understand the variation in the velocity with respect to the distance from the snout (Fig. 4 a&b).

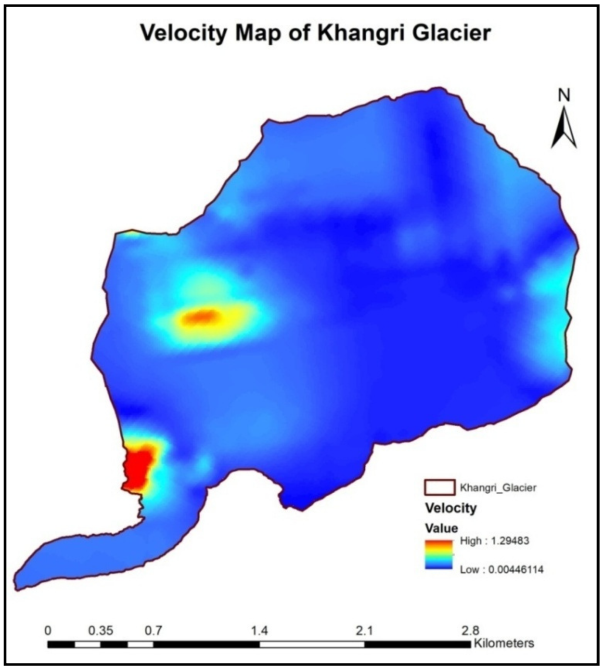


Fig. 4(a) Velocity pattern in Khangri Glacier

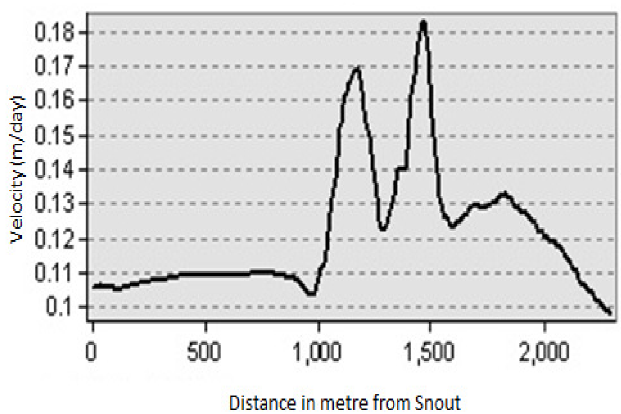


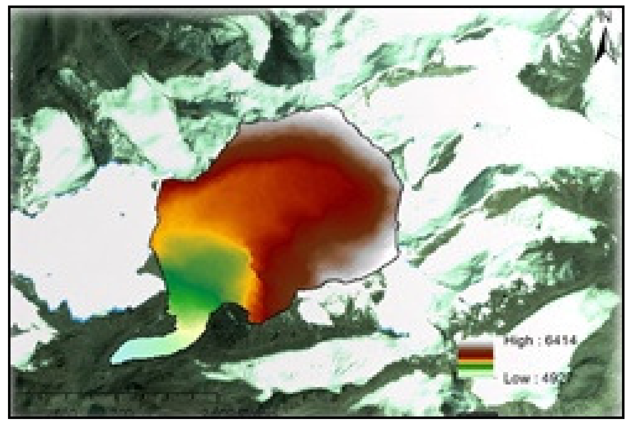
Fig. 4(b) Velocity profile graph of the glacier with respect to distance from snout

Mass Balance

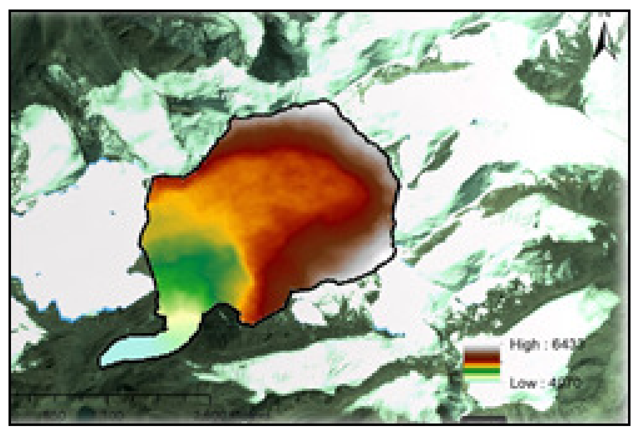
Mass Balance estimation using DEM differencing approaches

The term Mass balance means net gain and loss of ice from the glacier system for a given period of time. A glacier system thus for any point of time may be thought of as the product of how much mass it receives and how much it loses by melting. If the gain in ice mass is more than the loss due to melting, the glacier will advance and on the contrary, it will recede. If gain and loss are equal the glacier is said to be in the equilibrium state. Digital Elevation Model (DEM) data can be used to estimate the loss or gain of volume over a period of time.

Willis et al. (2012a) measured mass balance using the SRTM DEM and ASTER DEM from 2001 to 2011. DEM data (SRTM 2000) and ALOS PALSAR 2008 have been used for identifying changes with respect to elevation profile for the same area (Fig. 5 a&b). For climatic sensitivity studies of the glacier, the specific mass balance of glacier system can be derived by measuring the uncertainty in the ablation period balance using satellite-derived DEM data.



(a)



(b)

Fig.5 Volume estimation using (a) DEM (ALOS Palsar 2008) and (b) DEM (SRTM 2000)

A square fishnet of 75 m is created as a reference points in order to minimize the error of mean elevation of the glacier boundary using zonal statistics (Fig. 6). The area of the fishnet was further calculated especially for boundary nets and over each individual cells the mean elevation was calculated. The product of area and mean elevation gives the volume.

Table 1 represents the volume estimation of Khangri glacier for the year 2000 and 2008. RMS error was also estimated to assess the accuracy of the calculations.

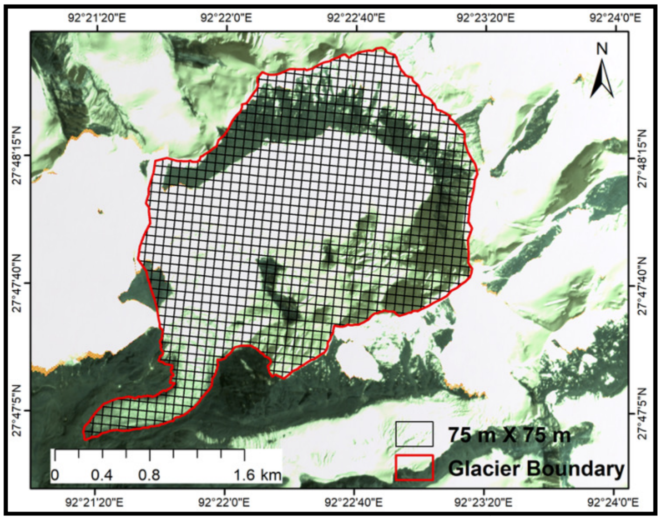


Fig. 6 DEM differencing using Fishnet grid over the glacier

Table 1: Volume estimation of Khangri Glacier

Satellite	Year	Resolution (m)	Volume (m^3)	RMSE Error (m)
SRTM	2000	30	34359708618.86	9.18 m
ALOS Palsar	2008	12.5	34143574960.071	4.85 m
Variation (Year 2008 – Year 2000)			-21,61,33,658.789	

It was found that, for the Khangri glacier, there is a loss of volume of 0.21613±0.0596 km^3 during 2000 and 2008. Dussailant et. al 2018 describes that formal uncertainties for mass balance estimates can be calculated taking into account six main sources of error: errors on dh/dt, errors in the glacier area, error on the density conversion factor, errors due to data voids, errors due to seasonal cycle sampling irregularities and departure from a linear trend. For density the error of ±60 kg m^{-3} was obtained from Huss (2013)

Water Discharge Measurement

In situ observation was made to develop the cross-section area of the stream through the general accepted approach of discrete measurement of stream surface from a constant straight rope at the above of stream tied at two banks. Generally, water flow depends on direct and indirect variables (slope, geology, patterns, climatic parameter, gravity and deposits). The cross section of the stream was calculated to be 2.48 m^2. The glacier river flow was calculated during the specific time (Table 2) by the flow method. Water discharge was derived using the relation:

$$\text{Water discharge } (Q) = A \times V \times CF$$

Where, A is area, V is the velocity of river and CF is the correction factor. The cross-section and velocity were established in 2018 and 2019 during field survey. To better understand the variation in discharge, the field survey was conducted during mid of ablation season in 2018 and end of ablation season in 2019. The average water discharge was found to be 3.39 m^3/s in 2018 compared to only 1.601 m^3/s in 2019 which shows the variation of water discharge at end of ablation season by more than 52% (Table 2).

Land Use/Land Cover Assessment

The LULC classification was carried out into six categories viz. Dry snow, wet snow, rocks, lakes, alpine meadow, shadow region. Pixel-based supervised classification approach was utilized where on an average 30 samples (spectral signatures) for individual classes were selected as the training data set. The classification was performed and with some manual correction overall accuracy of 86% was achieved and validated through ground survey and high-resolution satellite imagery platform through WMS service such as Google earth etc.

Table 2: Water discharge measurement of Khangri Glacier

Year	Date	Sectional Area (m^2)	Mean Velocity (m/sec)	Discharge (m^3/s)	Average Discharge (m^3/s)
2018	31-07-2018	2.452	1.33	3.147	3.39
	01-08-2018	2.396	1.236	2.861	
	02-08-2018	2.471	1.283	2.996	
	03-08-2018	2.601	1.091	2.831	
	04-08-2018	3.344	2.013	6.549	
	05-08-2018	2.805	1.126	3.211	
	06-08-2018	2.582	1.183	3.079	
	07-08-2018	2.471	1.093	2.764	
	08-08-2018	2.415	1.16	2.879	
	09-08-2018	2.378	1.38	3.591	

2019	21-11-2019	1.608	1.070	1.412	1.601
	21-11-2019	1.608	0.885	1.168	
	21-11-2019	1.663	0.915	1.463	
	22-11-2019	1.608	1.096	1.446	
	22-11-2019	1.627	1.165	1.556	
	22-11-2019	1.663	1.541	2.105	
	23-11-2019	1.645	1.203	1.625	
	23-11-2019	1.663	1.287	1.759	
	23-11-2019	1.682	1.354	1.872	
	24-11-2019	1.627	1.093	1.459	
	24-11-2019	1.645	1.222	1.651	
	24-11-2019	1.682	1.301	1.799	
	25-11-2019	1.645	1.077	1.505	

Khangri Glacier watershed spans a total area of 178.25 km^2. Out of this total area, the snow cover area (SCA) was calculated to spread across 55.38 km^2 area which is 31.11 % of the total study area; whereas other land cover categories that include rock, lake, alpine meadow/pasture land, shadow region occupied 69.89% area of the watershed (Table 3 & Fig. 7).

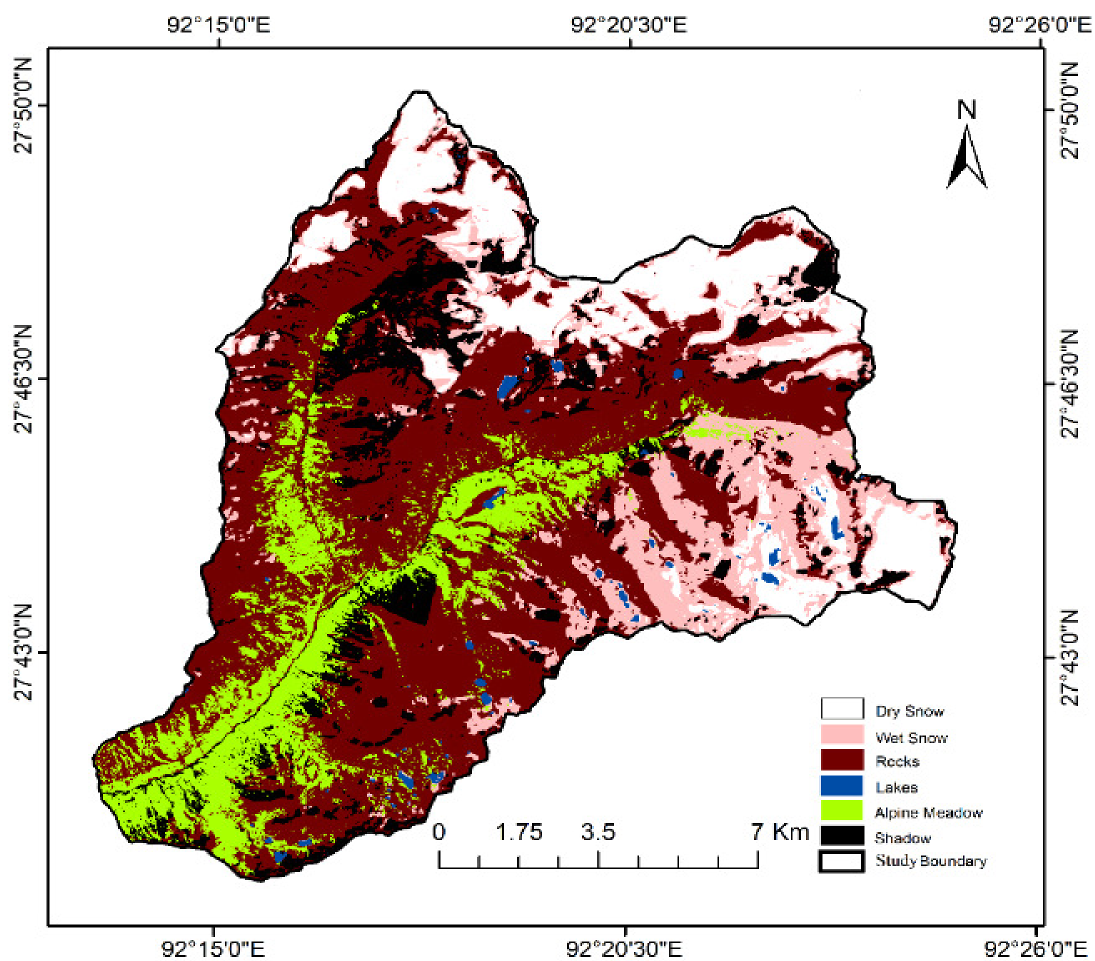


Fig. 7 Land Use/Land Cover classification of the study area

Table 3: LULC of Khangri glacier watershed

Classification	Area (km^2)
Dry Snow	29.58
Wet Snow	25.8
Rocks	61.92
Lakes	0.98
Alpine Meadow	35.31
Shadow	24.43

Snow Cover Area (SCA) Mapping

Glaciers greatly influence water resource management, vegetation, hydropower generation, flood etc. Therefore, snow monitoring is an essential process to know and understand the impacts of global warming on glaciers and then by its consequences on other water resources. The Normalized Difference Snow Index (NDSI) is widely used for snow-cover mapping at large scales (Dozier 1989). NDSI method is a technique useful for snow identification and monitoring using multi-temporal data. Snow has a crucial impact in the glaciations process and depending on the retreating rate.

The determinaton of snow accresion and recede rate was measured by using spatio-temporal data of Sentinel 2B at 10m. Normalized Difference Snow Index (NDSI) is commonly used for extraction of snow cover area in the given satellite imagery. The average accresion was 46.73 km^2 in the accumulation period (December to March) and the recession was 51.77 km^2 in the ablation period respectively (Fig. 8 & Table 4). It is projected that the accumulation is estimated using the green and swir band of the satellite data product. Higher NDSI value corresponds to fresh snow.

Monitoring of snow line at the end of the ablation season

The snow line can be defined as the location where there is enough snow to balance ablation. On temperate glaciers, this is typically taken as the boundary between snow and glacier ice (Paterson, 1994). Determination of snow line on Khangri glacier was accomplished using only the cloud free temporal satellite datasets for different period for year 2018. The snow cover area was derived using the NDSI value over the different imageries and the intersection of all the datasets yielded the area that was covered with snow

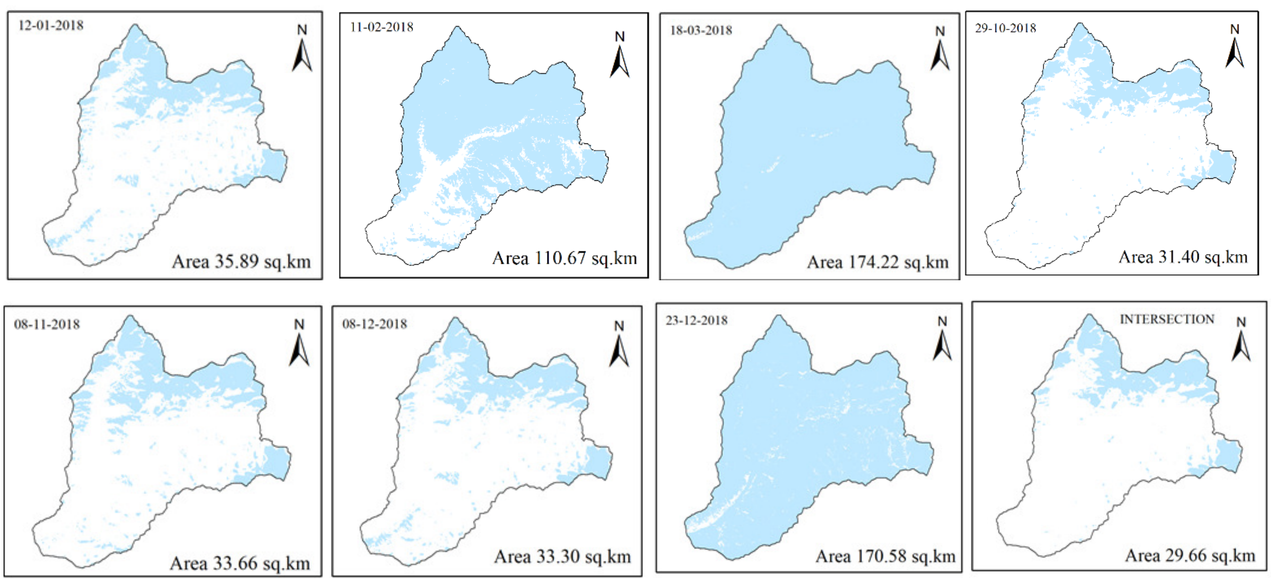


Fig. 8 Snow Cover mapping at accumulation and ablation periods

Table 4. Variations in snow cover area using NDSI

S.N.	Data Acquisition Date	Snow Cover (in km^2)	Snow Cover Balance	Seasonal Variation	Accumulation/ Ablation period
1	12.01.2018	35.89	-35.087	Recede	Accumulation
2	11.02.2018	110.67	39.693	Accrued	
3	18.03.2018	174.22	103.243	Accrued	
4	29.10.2018	31.40	-39.577	Recede	Ablation
5	08.11.2018	33.66	-37.317	Recede	
6	08.12.2018	33.30	-37.677	Recede	Accumulation
7	23.12.2018	170.58	99.603	Accrued	Accumulation

throughout the year. We observed that snow line lies on 5160 m elevation where permanent snow cover lies throughout the year.

CONCLUSIONS

Khangri glacier is situated at a high altitude of approximately 6300 m making it difficult to access. However, the field visits on the glacier provided the useful inputs to study the snout position and water discharge from the glacier. Further it also helps in ground truthing of the RS based observations or findings. As evident from the snout monitoring through field survey for years 2017, 2018 and 2019 as well as archival high resolution Google earth data at 0.5 m for year 2013, 2015 and 2016, it was observed that the glacier is in an equilibrium state and has not been showing much recede. Moreover, the reason of higher recede between the year 2018 and 2019 could be attributed to the time of data collection. Though the effect of climate change in the Himalayas cannot be denied, present findings of glacier mass balance of the Khangri glacier and snout position need to be studied further to arrive at any specific conclusion with respect to impacts of climate change on Khangri glacier. Care has been taken to estimate the remote sensing based observations and is validated on ground for their accuracy which is close to 85%. However, the better resolution satellite data products can further improve the accuracy. Also, to calculate the water discharge, the average depth of the streams for the cross section measurement has been obtained on regular interval of 0.6 m, which can be further improved if the depth is measured at closer intervals.

FUTURE SCOPE OF WORK

The velocity computed using the GIS platform may be validated on the ground through the installation of stakes and its temporal measurement. The availability of high-resolution imagery and better DEM data can further improve the accuracy. The water sample may be collected at regular time intervals to measure the physico-chemical characteristic of the water in the stream. Temporal analysis of high-resolution satellite imagery may help in identifying the status of equilibrium and snow line location which can be further analyzed to comparatively analyze the precipitation pattern in the accumulation season. Further meteorological characteristics can be studied to understand the impacts of increasing temperature on glaciers.

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