Assessment of Glacial Mass Balance of Changme Khangpu Basin in Sikkim Himalaya

A Thesis Submitted

To

Sikkim University

In Partial Fulfilment of the Requirement for the

Degree of Doctor of Philosophy

By

Amrita Singh

Department of Geography
School of Human Sciences
SIKKIM UNIVERSITY
Gangtok- 737102, India

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Date: 31/08/2020

DECLARATION

I, **Amrita Singh**, hereby declare that the research work embodied in the thesis titled **"Assessment of Glacial Mass Balance of Changme Khangpu Basin in Sikkim Himalaya"** submitted to Sikkim University for the award of the **Degree of Doctor of Philosophy**, is my original work. The thesis has not been submitted for any other degree of this University or any other University.

Amrita Singh

Amrita Singh

Roll Number: 12MPGP01

Registration Number: 14/Ph.D./GOG/05

Name of the Department: Geography

Name of the School: Human Sciences

6 माइल, सामदुर, तादोंग - 737102
गंगटोक, सिक्किम, भारत
फोन-03592-251212, 251415, 251656
टेलीफैक्स - 251067
वेबसाइट - www.cus.ac.in

सिक्किम विश्वविद्यालय
SIKKIM UNIVERSITY

6th Mile, Samdur, Tadong-737102
Gangtok, Sikkim, India
Ph. 03592-251212, 251415, 251656
Telefax : 251067
Website : www.cus.ac.in

(भारत के संसद के अधिनियम द्वारा वर्ष 2007 में स्थापित और नैक (एनएएसी) द्वारा वर्ष 2015 में प्रत्यायित केंद्रीय विश्वविद्यालय)
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All the assistance and the help received during the course of investigation have been duly acknowledge by her.

We recommend this thesis to be placed before the examiners for evaluation.

Dr. Uttam Lal
(Supervisor)
Department of Geography
School of Human Sciences

Dr. Rakesh Kr. Ranjan
(Joint-Supervisor)
Department of Geology
School of Physical Sciences

Dr. Sohel Firdos
(Head)
Department of Geography
School of Human Sciences

अध्यक्ष
Head
भूगोल विभाग
Department of Geography
सिक्किम विश्वविद्यालय
Sikkim University

6 माइल, सामदुर, तादोंग - 737102
गंगटोक, सिक्किम, भारत
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सिक्किम विश्वविद्यालय
SIKKIM UNIVERSITY

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6th Mile, Samdur, Tadong-737102
Gangtok, Sikkim, India
Ph. 03592-251212, 251415, 251656
Telefax : 251067
Website : www.cus.ac.in

Date: 31/08/2020

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Submitted by ***Amrita Singh*** under the supervision of ***Dr. Uttam Lal (Assistant Professor, Department of Geography, School of Human Sciences, Sikkim University)*** and ***Dr. Rakesh Kr. Ranjan (Assistant Professor, Department of Geology, School of Physical Sciences, Sikkim University).***

Amrita Singh 31/08/2020
Signature of the Scholar

Countersigned by Supervisor

Ranjan 31/08/2020
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Roll No. — 12MPGP01

Thesis Title — "Assessment of Glacial Mass Balance of Changme Khangpu Basin in Sikkim Himalaya."

Supervisor's Name

Dr. Uttam Lal

Joint Supervisor

Dr. Rakesh Kr. Ranjan

Reg. No. — 14/Ph.D/GOG/05

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Amrita Singh

Dedicated to my Mother and Father

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ABBREVIATIONS

AAR:	Accumulation Area Ratio
AOI:	Area of Interest
ASTER:	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AWiFS:	Advanced Wide Field Sensor
CCGC:	Central Crystalline Gneissic Complex
CK:	Changme Khangpu
CKB:	Changme Khangpu Basin
DEM:	Digital Elevation Model
ELA:	Equilibrium Line Altitude
ERA:	European Environment Agency
GDEM:	Global Digital Elevation Model
GLOF:	Glacial Lake Outburst Flood
GPS:	Global Positioning System
GSI:	Geological Survey of India
ICIMOD:	International Centre for Integrated Mountain Development
IHR:	Indian Himalayan Region
IPCC:	Intergovernmental Panel on Climate Change
ISM:	Indian summer monsoon
IUCCCC:	Inter-University Consortium on Cryosphere and Climate Change
LISS:	Linear Imaging Self-Scanning Sensor
MODIS:	Moderate Resolution Imaging Spectroradiometer
NSIDC:	National Snow and Ice Data Centre
PWR:	Physical weathering rate
P-XRD:	Powder X-ray Diffraction

RGI:	Randolph Glacier Inventory
SCA:	Snow Cover Area
SLA:	Snow line altitude
SMB:	Specific Mass Balance
SSL:	Suspended Sediment Load
SSY:	Suspended Sediment Yield
TRMM:	Tropical Rainfall Measuring Mission
TSS:	Total Suspended Sediment
UIB:	Upper Indus basin
UNESCO:	United Nations Educational, Scientific and Cultural Organization
UNEP:	United Nations Environment Programme
USGS:	United States Geological Survey
UTM:	Universal Transverse Mercator
WD:	Western Disturbances
WGMS:	World Glacier Monitoring Service

Chapter I

Introduction

I.1 Introduction

Mountain glaciers being an integral part of the cryosphere constitute one of the vital components of Earth's natural system. They are the prime reserves of fresh-water and amass about 75% of the world's freshwater (Sharma et al., 2013, Jansson et al., 2003). High sensitivity of glaciers to changes in the climatic environment renders them excellent indicators of prevailing climatic changes (Kaab et al., 2012). Over decades, glaciers all over the world have been experiencing recession at varying intensities and are most explicit evidences of global warming (Haeberli, et al., 1999; Oerlemans, 2005; Paul et al., 2007; IPCC, 2007; Bhambri et al., 2011). However, detailed glaciers ice mass variation data are still lacking for most parts of the world (Intergovernmental Panel on Climate Change, IPCC, 2007). In view of the vastness and inaccessible nature of the mountain glaciers, remote sensing is perhaps the only effective tool for their comprehensive and repetitive data acquisition in a cost-effective manner (Kulkarni et al.,2002; Bhambri and Bolch, 2009; Adina, 2009).

The Himalaya- 'Third Pole' are also known as water-towers of Asia supporting billions of lives downstream; these are also the climate driving force for the entire Asia (Dyurgerov& Meier, 1997; Immerzeel et al., 2012). Fragile ecology of the mountain system would undergo a drastic change, if there are changes in the climate (Dyurgerov & Meier, 2005). Anthropogenic changes have led to more demand for the water as well as other environmental resources in the modern industrial world.

The Himalaya covers around 10% of ice (glaciers and ice niches), and cryosphere area which could be as much as 20% more than solid glacier cover (Srivastava, 2012; Jones et al., 2017). The World Meteorological Organization (WMO, 2009) has reported that the polar areas have already undergone rapid decrease in snow and ice, thus, releasing methane from permafrost regions and also causing sea-level rise. The role of the cryosphere in controlling temperature through albedo effect is also an important aspect to understand the glacier formation, melt water discharge and glacier–climate interaction (Paterson and Cuffey, 1994; Vaughan et al., 2013, Gabbi et al., 2015). The consequences of the loss of Himalayan cryosphere on the society invite immediate attention and necessary evaluation of all these environmental parameters, so that a resilient and robust future plan could be drawn.

It is observed that a widespread glacier recession has been occurring over the past half century and has accelerated since the early 1990's in conjunction with the post 1970's warming trend (Mayewski and Jeschke, 1979; Kundzewicz et al., 2007). The impact of glacier shrinkage on ecological system, economic and social aspects are multi-faceted because of the fact that surge of glacial meltwater into rivers will be transient in terms of difference in melting and its total contribution to the river system (Kundzewicz et al., 2007). In concurrence with glacier shrinkage, many of these systems will suffer from altered precipitation regimes, drought, and reduced snowpack, further exacerbating the effects of climate change on water supply (Barnett et al. 2005; Lutz et al., Stewart 2009).

Large variability in topographic extent with different climatic zone over the Himalayan arc makes Himalayan glaciers responding heterogeneously in terms of mass balance, retreat rate and response to the climate variation (Hewitt, 2005; Kamp et al., 2011; Scherler et al., 2011; Bhambri et al., 2017). Himalayan glaciers are mostly nourished by (i) Westerly Disturbance (WD) arising from Mediterranean and Caspian Seas. WD brings large amount of precipitation in winter over western Himalaya and diminishing amount over eastern Himalayan and (ii) Indian Summer Monsoon (ISM) which significantly contributes solid precipitation over central and eastern Himalayan glaciers (Benn & Owen, 1998). The Indian Himalaya covers Karakoram, the western Himalaya, the central Himalaya and the eastern Himalaya that contain more than 9,575 glaciers (Raina and Srivastava, 2008).

Most of the high-altitude Himalayan region experiences snowfall and snow cover during winters, which play an important role in ecology of the region. Understanding of snow accumulation and ablation are important for utilization of Himalayan water resources as melting from seasonal snow cover during summer time forms an important source of many rivers which originates from the Himalaya.

Global temperature rise can significantly influence glacial retreat. However, each glacier is likely to respond to the warming differently, depending upon their size, area-altitude distribution, orientation, and moraine cover (Sangewar and Shukla, 2009; Bhambri et al., 2013; Buri and Pellicciotti, 2018). Therefore, monitoring glacial extent and changes is vital as it will have intense effect on availability of surface and sub-surface water.

I.2 Research Gap

It has been observed that most of glacier related studies were focused on western and central part of Himalaya while the eastern Himalaya did not get much attention. When combining the data generated from field with the remote sensing technique, these studies are less in this part as compared to other parts of the Himalaya. Limited studies have been conducted on the northern most part of Sikkim especially on snow melt contributing to discharge in the area and associated rate of erosion. This part of Sikkim Himalaya also has inadequate study on geomorphology and processes associated with it. The foregoing gap prompted to take this study and also is an attempt to generate field-based data for this part of the Himalaya.

I.3 Study Area

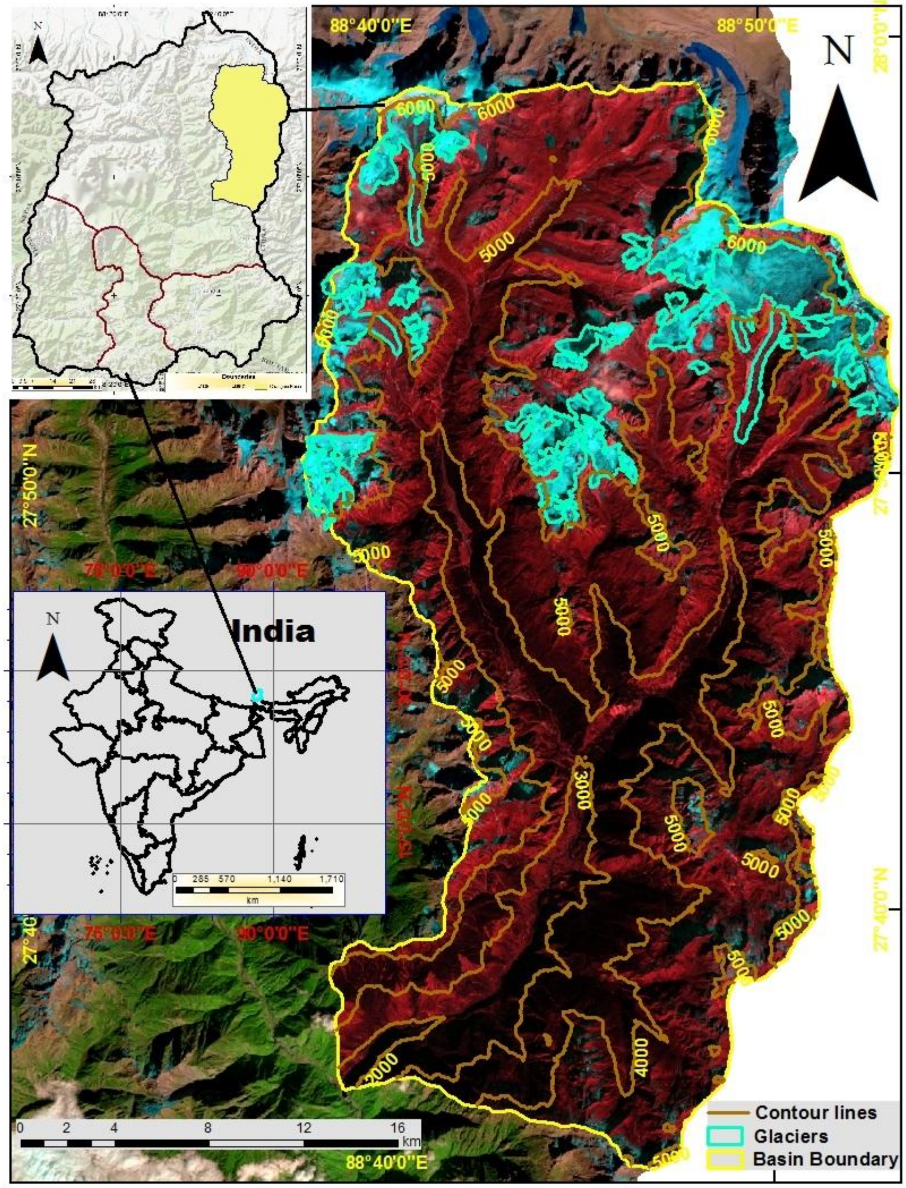
The present study has been carried out in the state of Sikkim in Eastern Himalaya. The state shares international boundaries with three countries namely, Nepal in the West, China in the North and Bhutan in the East. 'Changme Khangpu Basin' covering an area of 792 km^2 has been selected for the study located in the north district of Sikkim (Fig. I.1). The basin extent is from $27^0 35'$ N to 28^0N latitude and $88^0 35'$ E to $88^0 55'$E longitude, starting from an altitude of 1540 m to 7000 m above sea level (a.s.l). It includes many debris covered glaciers, hanging glaciers, clean glacier and rock glaciers. Although, it has many tributary rivers contributing to the main river which flows through the Lachung village but rivers origination from Changme Khangpu basin are few of the source glaciers of *Lachung Chhu*, a tributary of river Teesta.

I.4 Objectives

In order to understand the ongoing climatic variation and associated changes over the Himalayan glaciers, the present study has focused on the Changme Khangpu basin to probe on assessment of glacial mass balance with the following objectives:

- To map the glaciers and landforms in the Changme Khangpu basin and the processes governing it.
- To examine the seasonal, annual and altitudinal variations in Snow Cover Area (SCA) in the basin.
- To study the river discharge (Q) and rate of erosion and Total Suspended Sediments (TSS) in the basin.
- To estimate the mass balance of glaciers in the Changme Khangpu basin.

Fig. I.1: Location map of study area in Sikkim Himalaya, India showing Changme Khangpu basin boundary, glacier boundaries and contour height, overlaid on Landsat 8 OLI/TIRS image, 18 January 2018, 30 m spatial resolution.



I.5 Research Questions

- Has there been considerable variations in the seasonal and altitudinal Snow Cover Area in the Changme Khangpu Basin?

- 2. What is the rate of glacier melting and discharge accelerating erosion process in the basin?

I.6 Database and Methodology

I.6.1 Database

Primary sources of data are generated from field studies with the help of instruments like GPS, Differential Global Positioning System (DGPS), water sampler, filtration unit and sediment weighing balance. The secondary data consists of Geological Survey of India (GSI) maps, Survey of India Maps, Department of Mines, Minerals & Geology maps, remote sensing data such as Landsat TM, ETM+, LISS-III, MODIS images for the study of snow cover for 18 years (2002-2019), and AWiFS images.

I.6.2 Methodologies

I.6.2.1 Mapping Glaciers and Estimating Snow Cover Area

The mapping of glaciers in the basin has been done with the help of Survey of India (1962-63) topographical sheets, DGPS and GPS, and a set of satellite imageries. Satellite images such as SRTM, ASTER DEM, Cartosat v3 was used to map glacier terrain and elevation in ERDAS imagine 2015 and GIS (ArcMap 10.2), Landsat TM and ETM+ and OLI images, IRS- LISS-III, MODIS, AWiFS and Sentinel-2 MSIL1C for mapping glacier boundaries and related features. The glacier mapping has been done using semi-automated method and manual delineation of the boundary with the help of Landsat 8 images, Sentinel-2, Google Earth Pro, GPS points and detailed field survey. Snow Cover Area (SCA) (seasonal, annual and altitude-wise) is estimated with the help of MODIS 8-day Terra composite snow products (MOD10A2). The data is further compared with the previous study on Sikkim Himalaya (Teesta basin) by Basnett and Kulkarni (2011). Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index

(NDWI), Normalized Difference Snow Index (NDSI) (Kulkarni, et al. 2002; Kulkarni, et al. 2004) are few indexes which was used to estimated the snow cover as well as delineate the glacier boundary in the basin. The different indexes were estimated using following equations:

$$\mathbf{NDSI} = \frac{\text{Green} \ - \ \text{SWIR}}{\text{Green} \ + \ \text{SWIR}}$$

$$\mathbf{NDVI} = \frac{\text{NIR} - \text{RED}}{\text{NIR} + \text{RED}}$$

$$\mathbf{NDWI} = \frac{\text{NIR} \ - \text{SWIR}}{\text{NIR} \ + \text{SWIR}}$$

I.6.2.2: Discharge and Rate of erosion Analysis

(a) Discharge

Discharge (or surface runoff *Qs*) refers to the horizontal water flow occurring at the surface in rivers and streams (Brown, 2005). For the study of rate of discharge in the basin Float method has been used where discharge (Q) is measured with help of Area (A=cross-section area) and Velocity (V). The amount of water passing a point on the stream channel during a given time is a function of velocity and cross-sectional area of the flowing water (Rai et al., 2020).

$$\mathbf{Q} = \mathbf{A} * \mathbf{V} \qquad \textbf{(i)}$$

where, **Q** is stream discharge (volume/time), **A** is cross-sectional area, and **V** is flow velocity.

This method measures surface velocity. The idea behind these studies is to measure the time taken by the object to float a specified distance downstream. In general, surface velocities are typically higher than mean or average velocities. The steps for the data collection are following:

1. A specific point of the river has been chosen for the measurement of discharge where the undulating surface is minimum.
2. The starting and ending point was marked from the center point of bridge on a distance of 5-7 meters for both the sides.
3. The sample is collected on hourly basis from 7 am in the morning to 6 pm in the evening using a float, and the process was repeated three times every hour. The water level (W/L) of the river was also measured hourly. The calculation of final discharge was than done using the above equation (i).

(b) Rate of Erosion

The water sample was collected on seasonal basis for 2 years (2017 and 2018) on Nylon filter paper twice a day at 8 am and 5 pm. The Nylon filter paper was first kept in desiccators for the moisture absorption for a day and then the weight of the filter paper was taken using weighing balance. The collected water was then filtered using filtration unit and dried at room temperature. The dried filter paper having sediments was than weighed using the same weighing balance for its final weight and to find the amount of Total Suspended Sediments (TSS).

After getting the absolute value for both the processes, the final sample was put forward for the analysis, developing a relationship between rate of erosion and discharge in the basin.

I.6.2.3 Estimation of Mass Balance of Changme Khangpu basin

The Equilibrium Line Altitude (ELA)/ Accumulation Area Ratio (AAR) method is a useful tool to determine the mass balance of remote Himalayan glaciers. In this method, the ELA is demarcated for every single year for the duration of study taken to differentiate between accumulation and ablation zone of glacier. The ELA demarcation was done using remote sensing method and multiple satellite imageries from the year 2008 to 2019. The set of satellite images used for ELA demarcation includes LISS-III, Landsat 7 and 8, Sentinel-2A. These satellite images were taken at the end of melt season between September and October. The Cartosat-1 DEM is also used to know the elevation of the ELA on the glacier. Once the accumulation zone is demarcated, the AAR is calculated to understand the ratio of accumulation zone over the total glacier area. The AAR helps to under the gain or loss in mass of glacier for every single year.

I.7 Chapterization

The thesis was organized into eight chapters and each chapter presented by Section, subsection and paragraphs.

First chapter describes the importance of study of glaciers and the changes associated with climatic variation. It explains the objective of this research which is mainly focused on glacier and snow monitoring, sedimentological study as well as mass balance of glacier in the basin. It also highlights the methods and databases opted for present study.

Second chapter focuses on the review of literature on previous glacier inventories both globally and regionally. It takes into consideration the study on glacier mapping, snow monitoring, and the use of recent techniques based on field and remote sensing methods. It presents the most highlighted studies in this region and in other parts of the Himalaya and helps to understand the variation among them.

Third chapter gives the background of the Changme Khangpu basin in Sikkim and the associated landforms. A detailed geomorphology of the basin and different altitudinal zone based on field investigation, vegetation and temperature change were also described. This chapter also gives an overview of inventory of glaciers present in the basin and the associated change in the areal extent of the glacier over the decade.

Fourth chapter connects the landforms with the processes taking place in the glacierized basin through glacial and glacio-fluvial activities. The grain size, textural and mineralogical analysis of the glacier deposits has been done to know the process of formation and also glacio-fluvial activity in the region. In addition, detailed study of glacio-fluvial sediments from river channel covering a long route has also been studied in the region.

Fifth chapter has been followed by the study of discharge rate with the help of rating curve/ hydrographs and generating the relationship with erosion rate/ physical weathering rate in the basin. This will help in understanding the nature of sediment flow in the glacierized catchment of Changme Khangpu basin along with study of process of formation of sediments in the previous chapter.

Sixth chapter described the results of seasonal, annual and altitude-wise Snow Cover Area (SCA) in the basin. The detailed variation in snow cover were presented using remote sensing method during 2002-2019. It gives the variation in snow cover in summer and winter seasons and its relation with temperature and also compares the study with the whole Teesta basin based on earlier studies.

Seventh chapter focuses on the study of mass balance observation, and describes the loss or gain in glacier mass and change in pattern of ELA between 2008 and 2019. The annual balance trend has been discussed comprehensively. A comparison has also been done based on few previous studies.

In **chapter eight**, the thesis is concluded by providing the major finding of all the previous chapters. The short summary of the overall thesis is also presented. The study shows the retreat of glaciers in the basin as well as the physical processes are more dominating in the area. The landforms are result of both glaciers and glacio-fluvial activities and both are active agents in the basin. The study also gives an idea of changing snow cover pattern, that snow cover in the summer has increased over the decades and a decrease in winter snow cover areal extent. The focus is also made to address the future implications and attempts which can be made for further study.

Chapter II

Review of Literature

Mountain cryospheric systems are among the key areas to understand the effects of the global climate change (Hock et al., 2005). Due to naturally dynamic character, the geo-ecosystems of mountain systems are sensitive and vulnerable to weather and atmospheric variation (Messerli & Ives 1997; Thayyen and Gergan, 2010; Thayyen et. al., 2010). Further, regional climate models predict that the change in certain climate elements such as air temperature, moisture source and albedo, will be accelerated within mountain systems as compared to predicted global means (IPCC 2007). At the same time, those mountain systems and their forelands are the living space for considerable part of the global population. Therefore, any climate change that influences the hydrological cycle and increases the potential for natural hazards needs to receive high attention (Winkler et al., 2010).

The present chapter gives an overview of existing debates on mountain environment and cryospheric studies focusing on the Himalayan glaciers and changing scenarios. The works cited here are obtainable and gives a substance of global and Himalayan glaciers with the idea, scope and accessibility of remote sensing based study in the higher and rugged mountainous terrains where field based study generally lacks. It also highlights the cryospheric studies in parts of Sikkim Himalaya and the gap between these studies.

II.1 Global Distribution of Mountain Glaciers

The glaciers mass balance study is necessary to evaluate the rate of shrinkage over a period of annual to decadal and to infer impact of climate change. Glacier mass balance can be estimated by using glaciological, geodetic and hydrological methods. These techniques are applied all over the world for glacier monitoring (Cogley, 2011). Studies conducted by Zemp et al. (2009) and Bolch et al. (2012) analyzed mean specific mass balance of Indian Himalaya and other mountain glaciers (e.g. Andes, Alps) and found that most of the mass balance series are negative. However, the global glacier mass balance records are still incomplete owing to the basis of time series and required additional updates. This is necessary to strengthen the global glacier databases used for climate interpretations and sea level rise assessment (Dyurgerov & Meier, 1997; Hoelzle et al., 2003; Meier et al., 2007; Braithwaite, 2009; Zemp et al., 2009). According to Winkler et al. (2010) any climate change or any variation in individual climatic elements such as precipitation and air temperature, displays its impact at first in the form of related changes of the glacier mass. Abbermann et al. (2009) have clearly demonstrated the potential of high-resolution LIDAR DEMs as reliable methods to obtain changes in glacier area and volume in comparison with older glacier inventories. Changes in the glacier length are driven by the changes of the glacier mass balance and modified by the related mass flux/ glacier flow. Climatological, spatial and temporal diversity is reflected in glacier mass balance of Southern Norway, Otztal Alps, Austrian Alps and Southern Alps, New Zealand. Hence, it is unrealistic to assume that single glacier can be representative for a whole mountain system and confirm regional or global trends. Respectively, there is no alternative to meet the challenge of the significant spatial and temporal diversity of mountain glaciers with their response to climate change.

Moreover, mountain glaciers are one of the sensitive probes of local climate; thus, they present an opportunity and a challenge to interpret climates of the past and to predict future changes (Owen et. al., 2008, 2009). Besides, glaciers can constitute hazards, including GLOF's, changes in magnitude and timing of runoff and through worldwide loss of glacier ice-a global rise in the sea-level change (Kaab et al., 2005).

II.2 Himalayan Glaciers

Indian Himalayan glaciers including Lahul-Spiti, Kolahoi, Nanga Parbat, and Garhwal, show consistent retreat throughout the period, while Trans-Himalayan glaciers i.e. north side of the Karakoram and Batura Mustagh and Rakaposhi-Haramosh, display a major period of advance from AD 1890 to 1910 (Mayweski et al., 1979; Paul et al., 1989; Bhambri and Bolch, 2009; Latief et al., 2016). Hindu Kush Himalaya (HKH) covers India, Pakistan, China, Nepal and Bhutan and measured an area approximately 3500 km^2 northwest to southeast & northeast to southwest, respectively (Bajracharya et al., 2011). It has been analyzed that short to medium length glaciers (<30 km) display changes in the position of their termini in the range of 1 to 40 m yr^{-1}. Long glaciers (>30 km) display smaller magnitude changes in termini position up to 10 m yr^{-1} whereas the smaller glaciers tend to respond faster to any kind of environmental and climatic changes (<5 km). Several glaciers anomalously display high rates of advance or retreat, this anomalous character of glaciers is believed to be due to surging (Hewitt et al., 2005; Bhambri et al., 2017). It has also been assumed that the glaciers in the Himalaya and Trans-Himalaya are influenced by changes in the influx of moisture and heat and by inter-annual variations in the character of the monsoon.

Glaciers are a useful indicator of climate change in high mountain environments and have a significant influence on regional water availability. Despite the hydrological importance of glaciers for the adjoining low lands, data on the glaciers of the Himalaya, Karakoram and Hindu Kush ranges are sparse and inconsistent (Schmidt and Nusser, 2012). Studies suggests that (Armstrong, 2010), there is lack of long term-series and field investigations especially for glaciers at higher altitudes. The study deals with the Trans-

Himalayan region of Ladakh in the north-west India, and it has been said that this region may be located at the interface between shrinking and advancing glaciers. Here, a multi-temporal remote sensing approach based on satellite images namely Corona, SPOT, and Landsat is used to analyze areal changes of glaciers and to measure rate of retreat of glaciers.

According to some other studies, the impact of variable debris cover has also to be considered in the analysis of glacier changes (Scherler et al., 2011; Kaab et al., 2015; Pratap et al., 2015; Mal et al., 2019). Clear method has been mentioned to detect and analyze recent glacier area and length changes with the application of multi-temporal remote sensing. The dataset includes conventional satellite imagery from sensors such as Landsat and SPOT which allowed landscape monitoring since the required year and Corona images from the early U.S. military reconnaissance survey dating back to the 1960s (Racoviteanu et al., 2008). To minimize effect of seasonal snow-cover, images from period between the end of the ablation season and the first snowfall event are optimal and taken into consideration (Pandey et al., 2013; Mott et al., 2018). In general, the studies suggest that overall western, central, and eastern Himalaya experienced vast thinning of glaciers on regional level during the last decade - 2000s (Kääb et al., 2012; Bolch et al., 2012; Gardelle et al., 2013). On the contrary, Karakoram region showed slightly mass gain during almost similar period (Gardelle et al., 2012).

II. 3 Remote Sensing of Glaciers and Snow

Remote Sensing and GIS based monitoring of glaciers has gained utmost importance with time owing to large aerial coverage with lesser human efforts (Gao and Liu, 2001; Cracknell and Varotsos, 2011; Shrestha et al., 2016). Because of the rugged terrain and unpredictable weather patterns in the Himalayan regions, it is very difficult to access and have continued focus on these areas. Remote sensing techniques had made it easier and is one of the ways to study the glacier response over the long period of time (Altena and Kaab, 2017). The combination of remote sensing techniques and field investigations with ground control points can give more reliable and accurate dataset on the health of glaciers all over the world (Racoviteanu at al., 2008; Rabatel et al., 2017). Remote sensing has also helped in overcoming the difficulties of meteorological data as many regions in Himalaya lacks weather stations due to its difficult and inaccessible terrains. Studies show that remote sensing derived meteorological data is good replacement in the high mountainous terrains where the ground based data's lacks (Murtaza and Romshoo, 2017; Romshoo et al., 2018). The understanding of hydrology, climatology and glaciology is constrained due to the lack of these meteorological data (Dar and Romshoo, 2012; Blum et al., 2015).

One of the earliest studies were carried out using Landsat Multi-Spectral Scanner (MSS) imagery, where glacier extent was mapped (O'Brien and Munis, 1975; Salomonson and Koffler, 1984). Later on, False Colour Composite (FCC) (visible and near-infrared satellite images) made it more useful and precise to map glacier features such as glacier boundary, accumulation area, ablation area, equilibrium line and glacier-dammed lakes (Ostream, 1975; Ventura et al, 1975; Kulkarni, 1991). Because of the difference in their spectral reflectance, these features on satellite images are more visible and could be marked by far for glacial and non-glacial features (Shukla and Ali, 2016). As obtained from satellite images, spectral reflectance of accumulation area is high in bands 2, 3 and 4 in Landsat TM and IRS LISS-II. On the other hand, for ablation area, the spectral reflectance in band 2 and 3 is higher than surrounding terrain but lower than vegetation in band 4; therefore, this gives blue-green tone on FCC (Dozier, 1984; Hall et al, 1988). The spectral characteristics helps in differentiating the glacial and non-glacial features on satellite images.

II. 3.1 Glacier Mapping and Monitoring

Remote sensing studies over Himalayan cryosphere mostly aim at establishing digital glacier inventories to track the changes in glacier surface when compared to older map-based inventories (Kaul, 1999; Bhambri and Bolch, 2009). Given the mass and remoteness of glaciers in Himalaya, satellite imagery is considered to be a suitable means to attain a comprehensive and more frequent sampling of their evolution (Bishop et al., 2000). In western Himalaya, satellite images like SPOT-5, ASTER, SRTM-DEM (Shuttle Radar Topographic Mission-Digital Elevation Model) and field data have been used for the study of glaciers which is helpful in fulfilling the gap in continuous monitoring of glaciers (Kaab 2005; Berthier et al., 2007; Kaab et al., 2014).

Most of the authors have adopted the similar kind of methods and data for marking glacier boundaries and features using SPOT5, SRTM, ASTER DEMs, IRS- LISS II and LISS-III, Landsat, and also combination of remote sensing and field based investigations (GPS point and surveys, SOI topographical sheets) (Higuchi et al., 1980; Ageta and Satow, 1978; Muller, 1970; Kulkarni and Buch, 1991; Kaul, 1990; Ahmed, 1962; Basnett et al. 2012, 2013).

Since 1970's, with the launch of new space borne sensors like Landsat Multispectral Scanner (MSS), Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+), SPOT, Terra ASTER, the Indian Remote Sensing Satellite (IRS), and more recently the Advanced Land Observing Satellite (ALOS) launched in 2006, remote sensing method has made the study of glacier's in rugged terrain more approachable. Other optical sensors having high spatial resolutions like IKONOS, Quickbird and GeoEye, SPOT provide satellite imagery as suitable for detailed glacier studies at basin scales as aerial photography (Recoviteanu et al., 2008). The CORONA imageries (American intelligence spy satellite series) from 1960 to 1972 were declassified in 1995, and are available for some glacierized areas at USGS Earth Explorer (http://earthexplorer.usgs.gov) which is a sub-meter imagery. The optical remote sensing, with the launch of these satellite imageries with modified version, both at regional and global scale, has made it possible to do a continuous study of glacierised area and its features in rugged terrains using new techniques.

Similar study by Basnett, Kulkarni & Bolch (2013) shows the use of remote sensing and GIS techniques for the study of debris cover glaciers and glacial lakes in Sikkim Himalaya. Landsat Thematic Mapper (TM) (Level 1T) and IRS LISS III satellite images were analysed to map and monitor the glacier changes. Also, the LISS III images were co-registered to the Landsat images and used for delineating glacier boundaries. This study focuses on the use of false-color composite with band combination of red, near infrared (NIR) and shortwave infrared (SWIR) and a true color composite of red, green and NIR of Landsat TM/ETM+ and LISS III images, for the glaciers and lake boundary delineation. Normalized Difference Snow Index (NDSI) has also been [(NDSI) = (green-SWIR) / (green + SWIR))] applied on AWiFS image to eliminate non-glacier areas under mountain shadow conditions. According to study, the number of lakes, the area of debris cover and the size of moraine-dammed lakes have increased and this could further influence mass loss.

II.3.2 Monitoring Snow Cover Changes:

Perennial rivers in the Himalayan region initiate mostly as glacier melt runoff and snow melts (Singh and Singh, 2001) and is directly affected by climatic conditions also, be it a local or regional climatic condition (Adam et al., 2009). Glaciers of the central and eastern Himalaya are shrinking due to loss in glacier mass and glacier extent (Kulkarni and Karyakarte, 2014). As the melt water from seasonal snow, fed water to major rivers in parts of India like Indus, Ganga, Brahmaputra and fulfills the requirement of people, industries, agriculture and development, it is necessary to maintain sustainability of glaciers. These rivers are also considered a source of fresh water and are important in assessing the health of glaciers periodically (ICIMOD, 2011).

The complexities in the process of snow hydrology is less understood due to largely due to the lack of hydro-meteorological data in high altitudes. According to the studies, only some efforts have been made to develop the relationship between snow cover area and runoff, but the detail studies have not been carried out yet (Ramamoorthi, 1986). For accurate estimate of volume of water stored in snow packs, its flow rate and snowmelt runoff, the snow cover depth and water equivalent are necessary parameters (Basnett et al., 2013; Krishna, 1996, 2005).

There are many techniques for snow mapping which includes: semi-automatic method of NDSI to differentiate between snow and ice, the NDWI for masking water bodies and the NDVI for differentiating between vegetation and other features. Besides these remote sensing techniques, there are some direct field based approaches to study snow cover changes, which includes snow meteorological data's and use of stakes and pits method. These methods are considered difficult in the rugged terrain of Himalaya and is one the reason that the study based on the ground observation are lacking in eastern part of

Indian Himalaya (Kulkarni et al., 2002; Racoviteanu, 2009). In this respect remote sensing techniques has gained huge ground. However, combination of both, ground observation as well as remote sensing technique will give a more accurate result. Few studies have been done using these two techniques together, for example- Gangotri glacier based on remote sensing and ground observation techniques was monitored using Indian Remote Sensing (IRS) LISS-III data in combination with field collected snow meteorological data for seven years (Negi et al., 2012). Monitoring of snow cover pattern and assessment of the possible changes in glacier health are required because glaciers are sensitive to climate and they are considered to be an indicator of climate change (Kulkarni et al., 1999; Basnett et al., 2011; Krishna, 2011). The complete analysis of snow cover has been carried out using satellite retrieved and ground observed data on seasonal basis. Daily snow-melt data such as temperatures- minimum & maximum, fresh snowfall and rainfall recorded from field observatory were analyzed for comparison or validation of snow cover area and snow characteristics. The topographic analysis was carried out using DEM with the help of Survey of India map-sheets. Terrain parameters such as slope, aspect and elevation were generated using DEM based on slope changes within glacier bed and glaciers constrained by topography.

The advantage of discriminating between snow and cloud pixel except high cirrus cloud, as cloud reflectance is high in SWIR region; NDSI is considered one of the effective methods for glacier and snow study. In addition, it can also take care of snow under mountain shadows (Kulkarni et al., 2004) and it also tends to reduce the influence of atmospheric effects and topographic effects (Salomonson and Appel 2004; Negi et al., 2009).

Snow cover in the state of Sikkim has been reported to be maximum in the month of February. Western disturbances have an influence on the snow peaks and precipitation in Sikkim Himalaya (Basnett and Kulkarni, 2019). Although, the timing of snow cover peaks differ across the Himalaya due to difference in weather pattern, for instance highest snow precipitation in Jammu is in the month of January. The study has been done with the help of 200 imageries of Advanced WiFS data of RESOURCESAT- following Normalized Difference Snow Index (NDSI) methods.

Most glaciers in mountainous region of the world have receded during the last 100 years, in response to climate variations (Hansen and Lebedeff, 1978). Himalaya has one of the largest concentrations of glaciers outside the polar region and some estimates suggest that the number could be as high as five thousand (Kulkarni and Bahuguna, 2001). The state of Sikkim in the midst of the eastern Himalayan region is surrounded by snow clad mountains of Nepal, China and Bhutan. Teesta basin of Sikkim Himalaya has 84 glaciers. Snow cover pattern has been analysed with Long Period Average (LPA) temperature and rainfall data. Long Period Average (LPA) temperature and rainfall trends influence snow accumulation and ablation pattern (Basnett and Kulkarni, 2011). The study indicates different snow accumulation and ablation pattern in Sikkim Himalaya as compared to the western Himalaya.

II. 4 Glacier Mass Balance

To understand and evaluate the rate of loss or shrinkage over a period of year and decade glacier's mass balance study is really need of the time and also to gather information about the impact of climate change. In recent years, remote sensing and GIS based study on glaciology has increased and as a result the area which are highly inaccessible are also being studied. In 1974 GSI initiated the first study using glaciological method in the Indian Himalaya (Raina et al., 1977) and carried out the study on fourteen glaciers but these glaciers have not been monitored for longer period (Srivastava, 2001 and Raina, 2010). This method is an in-situ measurement of accumulation and ablation area over the entire glacier during a year and the measurement is done using stakes and pits placed on the glacier surface. There are several methods for carrying out the mass balance studies, which has been used worldwide and methods widely used are as follows:

II.4.1 Field Methods

a) The Glaciological Method:

Glaciological method is the traditional method for the most accurate determination of mass balance by using stake networks (Ostrem and Stanley, 1966; Zubok, 1975; Koermer, 1986; Meier, 1961; Catasta and Smiriglla, 1993). It is the only method that provides undelayed and direct response of annual atmospheric variation for mass balance. It includes the net accumulation/ ablation data from each stake measurement within a time interval and the difference (m) is multiplied by the near surface density to estimate the mass balance of that point.

b) The Hydrological Method:

The mass balance of a glacier can also be calculated by estimating the annual accumulation and ablation from snow-accumulation and discharge data (Paterson, 1998). This is generally used for small drainage basin. Estimation of mass balance of a glacier by this method is considered to be relatively unreliable, as the adequate sampling of precipitation, runoff and evaporation of the glacier is difficult to record throughout the year in mountainous terrains. Maintaining a good gauging station for water discharge is expensive and also time consuming.

II. 4.2 Remote Sensing Methods

In-situ techniques generally used for measuring glacier mass balance have a tendency of labour intensive, expensive and provides very limited spatial coverage. Thus, satellite and air borne observations provide practical approach of obtaining meaningful mass balance studies at a regional scale and makes it possible to study glacier health.

a) The Flux- Divergent Method:

This method is combination of geodetic method with dynamic ice flow models to obtain spatial distribution of glacier mass balance with basal topography. The method was claimed to be promising because of increasing airborne and satellite techniques, but Bauder (2001) has mentioned that it fails because of lack of ability of the dynamic methods to provide accurate vertical ice velocities and the dependency of this method on expensive airborne instruments makes it more difficult as their availability are subject to weather conditions as well.

b) The AAR and ELA Method:

This method needs the accurate glacier area and Landsat TM/ETM+ can be used to determine the end of summer snowline by differentiating between the wet snow and ice (Bindschadler et al., 2001). The transient snowline altitude at the end of ablation season is used as a proxy for the equilibrium line altitude (ELA) (Rupal et al., 2014) and it can be used to estimate the accumulation area ratio (AAR) of the glacier.

c) ***The Geodetic Method:***

Geodetic method is considered to be the most successful approach in remote quantitative observations and for the estimation of glacier mass balance (Rignot et al., 2003). This method is based on the change in elevation over time (dh/dt) which can be translated into mass. Subtracting the surface elevation of a glacier and the extent of the glacier at two different time scale gives final volume change (Kaser et al., 2003). This change is further converted into mass by measuring the density of snow at different parts of the glacier. This method needs the DEM's obtained by aircraft, satellite imagery and by airborne laser scanning and also using topographic maps. For average mass balance, the satellite imageries must be over the period of minimum a decade. As this method is time saving and convenient, it has been used worldwide (Mareus et al., 1995; Salpano et al., 1998). It is believed to be one of the easy and simple way of monitoring glacier mass balance and applicable to determine only the average mass balance of the entire glacier.

The study of mass balance using geodetic method suggests that in western Himalaya glacier are losing mass rapidly (-0.53 ± 0.16 $m.w.e.a^{-1}$) in comparison to central and eastern Himalaya (-0.33 ± 0.14 $m.w.e.a^{-1}$) (Gardelle et al., 2013). Within a region, every glacier behaves differently depending on the varying topography and climate regimes, since field measurements are barely available, the basin level mass balance is necessary to study (Bamber et al., 2007; Gaddam et al., 2017).

Meteorological data also plays an important role in understanding the retreat or advance of a glacier as well as mass loss of glacier area and which can be a support for understanding the trend and future prospects related to snow and glacier area change. The loss of glacier area is found to be possibly caused by increasing temperature during the analysis of climate data (Basnett et al. 2013). At the same time, number of statistical techniques is used to understand the relationship between mass balance and meteorological variables particularly the correlation between glacier fluctuation and external climate variables (Dobhal et al. 2004; Kulkarni et al. 2002, Naithani et al. 2001; Singh et al. 2005), which according to him will be helpful to understand the relationship between glaciers and its fluctuations. The mass balance of the glacier is closely linked to kinematic response to seasonal and climatic change. The change is triggered due to the effect of the local topography particularly the high relative relief that induces change in micro-meteorological parameters such as change in accumulation of glacier mass at the surface of the glacier, change of energy input from atmosphere and change of geothermal heat flux.

The impact of inter and intra-annual variation in weather parameters on the health of glaciers has been studied for Naradu glacier in the Baspa Valley of Himachal Pradesh. Koul and Ganjoo in 2010 have done study on mass balance of Naradu glaciers which emphasizes on an annual estimation through residual accumulation and ablation techniques. It has been estimated by monitoring the ablation stakes fixed on glacier body at the end of the ablation season. Also, the assessment of the annual variation in weather parameters and its impact on glacier has been done with the help of automatic weather system. The sensors comprise of air temperature, humidity, speed and direction of wind, cloud, precipitation (snowfall and rainfall), solar radiation, sunshine hours and albedo.

Glacier volume also fluctuates in response to changes in precipitation seasonality even if no change in annual precipitation amount occurs, because of changes in glacier albedo and the volume that is able to accumulate (Naito et al., 2001). Many of the large glaciers in the Himalayan region are debris covered and have shown different behaviors from those of the clean glaciers. It is suggested that furthermore modeling studies should examine the dependence of the mass balance of debris-covered glaciers on precipitation condition.

Remote sensing techniques has made it more open for the researchers to use geodetic method for the mass balance estimation claiming to it be more convenient and rationalized results for remote areas as compared to the glaciological method of mass balance study. In Iceland optical satellite images from the ASTER sensor and Synthetic Aperture Radar (SAR) data from ERS-2 and Envisat ASAR has been used for glacial mass-balance study (Jaenicke et al., 2006). Inter-annual mass balance fluctuations were observed by comparing three radar images acquired in the late summer because winter radar images were not useful for mass-balance observations due to frequent surface melting, which prevents the transparency of the snow cover for C-band microwaves. The study has showed that remote sensing data are of great use for continuous mass balance monitoring of Myrdalsjokull glacier, Iceland. The combination of optical and radar satellite data proved to be very useful for mass balance investigations.

Kulkarni and Karyakarte (2014) suggests the combination of various methods helps in studying the mass balance of glacier for long and continuous such as- field data, AAR, ELA, and geodetic measurements. Himalayan glaciers have resulted in significant increase in mass wastage of glaciers in the last three to four decades. The cumulative loss of ice in these decades has been estimated at 19 ± 7 m. This study also shows the acceleration in the mean loss of glacier mass in Indian Himalaya which is around -9 ± 4 to -20 ± 4 Gt/year in decades 1975-1985 to 2000-2010. If this rate and speed of loss continues, it may influence the livelihood of people living in the mountains.

Hubbart et al. 2000, has followed an indirect methodology for determining the distribution of mass balance using remote sensing and ice-flow modelling. Mass balance has traditionally been estimated using the glaciological method, which involves interpolating labour intensive point measurements taken at stakes and snow pits across an entire glacier area over time. Geodetic method is an alternative to the glaciological method. The Geodetic method involves survey of the glacier surface over a given period to calculate the change in volume. The volume change can be well studied with the help of remote sensing methods which gives a precise result for change in the spatial pattern of surface elevation using Digital Elevation Models (DEMs).

During last decade, studies based on geodetic method suggest that western, central and eastern Himalaya has experienced vast thinning from regional level (Bolch et al., 2012; Kaab et al., 2012; Gardelle et al., 2013). On the contrary, Karakoram region showed slight mass gain during almost similar period (Gardelle et al., 2012). Studies also gives evidences of similarity between space based and field-based mass balance estimation in the western Himalaya (Berthier et al., 2007). Study on Pensilungpa Glacier in Zanskar valley has been done to estimate glacier thickness change using 2003 ASTER DEM and 1962 DEM generated by SOI contour map (Pandey et al., 2012). This study indicated increase in the glacier elevation in the accumulation zone mainly by 30 to 90 m and reduction by 30 to 90 m in the ablation zone.

Himalayan glaciers are more sensitive to climate change than other mountain glaciers in the world and as a consequence to increase in atmospheric temperature during the last century, deglaciation processes in Himalayan glaciers have enhanced at an alarming rate and are continuously experiencing the negative mass balance across Himalayan arc (Kulkarni et al., 2007, Raina, 2009; Sandhu et al., 2018). In recent years, the mass balance study in the Indian Himalaya has increased mostly in western and central Himalaya; where field study has continuously been done over decades. Eastern Himalaya is lacking the study and continuous glacier field measurement as compared to other parts of the Himalaya. Remote sensing-based method made it easier and accessible for researchers to study glaciers but level of accuracy and reliability is still unknown without comparison of the in-situ measurements.

II .5 River Discharge and Suspended Sediments Transportation

The volume of water that flows past a certain point in a stream over a specific period of time is usually termed as Discharge (Q). It is expressed in cubic meter per second (m^3 $s^{-1)}$. In the high Himalaya, rain, ice and snow are thought to control discharge of the large rivers (Immerzeel et al., 2009, 2010; Bookhagen and Burbank, 2010). Glacial-discharge contributions in the high-elevation Himalaya are more complex, but the few existing mass–balance studies (Kargel et al., 2011) and studies measuring the seasonal waxing and waning of glaciers suggest a significant glacial contribution to discharge (Bolch et al., 2011).

Snowmelt was found to be the most important water source during pre-monsoon season from March to May (Bookhagen et al., 2010), whereas rainfall and glacial melt become key contributors to river discharge during summers (Kaser et al., 2010). More than 50% of the annual discharge comes from snow that falls during the westerlies in the northwest and eastern Himalaya. Whereas, the central Himalayan rivers generally receive less than ~25% of their annual discharge from snowmelt, and are instead fed mainly by summer monsoon rainfall (Bookhagen and Strecker, 2012, Basnett and Kulkarni, 2011).

Earlier studies of snowmelt runoff in different parts of Himalaya- western, central and Karakoram, already highlights its importance and contribution to river discharge which also balances the runoff pattern. Snowmelt is the source of fresh water and source of living for the people downstream in domestic, economic, industrial and agricultural purposes (Akyurek and Sorman, 2002; Jain et al., 2008). Temperature is considered to be one of the important parameter in runoff estimation as it influences the snow and glacier melt pattern in these regions (Martinec, 1975; Prasad and Roy, 2005; Alam et al., 2011; Maskey et al., 2011). Increase in atmospheric temperature influences snowmelt and stream runoff pattern and is considered crucial for determining hydropower potential (Kulkarni et al, 2002a; Kulkarni et al., 2011; Rathore et al., 2009; Rathore et al., 2011).

Water discharge measurements can be done in several ways such as Bucket and stopwatch method, Surface velocity method (Welber et al., 2017), Two-Point method, Three-Point method and Manning's equation method, Velocity-Area method (Costa et al., 2006; Chitale, 1974; Schmidt, 2002) includes- Float method, Tracer method (Hull, 1958; Fischer, 1966) and Current meter (Sethi, 2018).

Fine sediment which include clay, silt and fine sand is generally the dominant component of a river's sediment load (Syvitski et al., 2000; Turowski et al., 2010), globally comprising about 90 percent of total sediment and a large fraction of the phosphorus and carbon flux to ocean (Milliman and Meade, 1983; Owens and Walling, 2002; Regnier et al., 2013). Suspended sediment concentrations measured at a given location integrate influences from all sediment sources and sinks above that point. Therefore, expected to depend on watershed characteristics such as topographic relief, vegetative cover, geology, rainfall intensity, temperature variation, level of glaciation, slope, and human impacts (Langbein and Schumm, 1958; Ahnert, 1970; Wischmeier and Smith, 1978; Summerfield and Hulton, 1994; Syvitski et al., 2000, 2014; Mueller and Pitlick, 2014). An important metric for characterizing the suspended sediment regime in river systems is the empirical sediment rating curve (SRC) (Asselman, 2000; Hu et al., 2010; Warrick, 2014). It describes the average relation between river discharge (Q) and suspended sediment concentration (SSC) or total suspended solids (TSS). Q-TSS relationships are unique characteristics of a river's sediment regime that symbolize the combined effects of erosion, transport and deposition occurring across the range of flows upstream from a point in the watershed (Mouri et al., 2014; Kumar et al., 2018; A. Kumar et al., 2018). Therefore, regional variation in Q-TSS relationships may offer insight into geomorphic processes and dominant sediment sources.

The hydrology of glacier regions for the most part is thermally controlled. Fluctuations in melting of snow and ice and the production of melt water is mainly due to variations in energy. Because of thermal threshold, snow and ice masses are prevented from entering the liquid phase until the critical melting temperature is attained. In high mountainous areas, over an annual discharge cycle, specific runoff is higher than in surrounding plains because of greater precipitation inputs and reduced evaporation. Because some of the precipitation accumulates in snow pack in winter at temperature below freezing point, much runoff is delayed from the time of precipitation until later in the year. Seasonal variations in the form of precipitation from winter snowfall to summer rain produce strong seasonal periodicity of hydrological event which influences quantity, quality and timing of drainage (Young, 1985).

Flows of rivers and streams in mountain are concentrated in spring and summer months, when water is released by melting of snow and glacier ice. In comparison winter discharges are very low, according to the duration of the temperature below freezing point. Mountain runoff, therefore, largely reflects change in heat energy available for melting and whether the melt is derived from seasonal snow cover alone or from a basin also containing perennial snow and glacial ice (Hasnain, 1999). The runoff from the glacier valleys in the Himalayan region is contributed by snow/ice melt and monsoonal rainfall, resulting in discharge peak in July/August (Hasnain et al., 2001). The potential of solute acquisition by melt water in the sub-glacial environment is several times higher than in other glacial environments. The reason favoring is due to (1) the slow transit time of water within the sub-glacial system (2) the availability of large amount of freshly comminuted rock flour and (3) the availability of reactive minerals, such as carbonates and sulphides in the fresh rock flour, which provides additional protons for chemical weathering (Tranter and Raiswell, 1991; Tranter et al., 1986, 1993; Brown et al., 1994, 1996; Collins, 1996).

The suspended sediment in glacial meltwater is by-product of mechanical erosion (Knudsen et al., 2007). Suspended sediment generated by glacier erosion is highest in the Himalaya as compared to other regions of the world (Hasnain and Thayyen, 1999). This may be due to high altitude, steep slope, active monsoonal rain as well as recent age of the Himalaya. The ongoing interactions of Indian and Eurasian plates maintain uplift, and high elevation ensures high level of precipitation and large glaciers. Steep, unstable slopes maintain sediment supply to the rivers of the subcontinent (Collins and Hasnain, 1995).

The amount of suspended sediment in meltwater is dependent on the nature and types of rock eroded, glacial abrasion and the rate of glacier melting. The discharge and amount of sediment varies from year to year depending on variable rates of supply of total sediment to the stream network, different source areas, and routing of sediment through the stream network (Gumell, 1982). The suspended sediment in glacial meltwater is more than non-glacial fed river. Embleton and King (1975) have observed a five-fold difference in sediment yield between the glacierised Hoffelsjokull river in Iceland and a nearby non-glacier fed river.

Harbor and Warburton (1993) demonstrated that the rates of erosion are higher for glaciated areas than non-glaciated areas. The presence of unsorted deposits of sediment found in the area is an indication of potential of glaciers in the production of sediment. A number of studies (Ferguson, 1984; Warburton, 1990 a, 1990 b) have demonstrated that specific sediment yield may increase downstream due to remobilisation of sediment pushed by active glaciers. A survey of sediment yield from 1358 drainage basins with an area ranging from 350 to 1,00,000 km^2 found that within particular climate zones sediment yield tends to be higher especially where glaciers are active (Jansson, 1988). Beside abrasion, plucking, quarrying, crushing and shearing are the physical weathering processes, which are responsible for release of sediment in glacial melt-water. The suspended sediment transport in the pro-glacial streams in the Himalayan uplands is controlled by glacial area, glacier activity (retreating), monsoon rainfall, and changing glacial drainage system (Hasnain, 1996).

Few authors like Chen et al. (2016), Steenhuis et al. (2013) also used correlation and multiple regression combined with spatial analysis and showed the relationship between precipitation, discharge and TSS and how these relationships change along different gradients. Sediment Rating Curve (SRC) commonly expresses Suspended Sediment Concentration (SSC) as a power function of discharge (Q) (Campbell,1975; Walling, 1977). Erosive rainfall, snowmelt and icemelt are the three major hydro-climatic variables which plays an important role in determining SSC in alpine environment (Costa et al., 2017, 2018).

Several scholars, Borland (1961), Ostrem (1975) and Collins (1979) have implied rating curves to describe and estimate level of suspended sediment transport in pro-glacial streams. Since the flow of water in a stream transports sediment, it follows logically to anticipate a relationship between the suspended sediment concentration and the discharge of the stream. It has been observed that the supply of sediments does not impose a constraint on the suspended sediment concentration discharge relationship. However, the results obtained from rating curves to estimate suspended sediment transport from glacial melt-water stream are very period specific. According to Collins (1989), the bulk of sediment delivery probably results from glacier sliding by bringing basal ice and deforming basal sediment from up-glacier in contact with flowing melt-waters or relocating conduits incised upwards into ice on the areas. Glacierized areas present an ideal environment to study water-rock interaction, since chemical weathering rates are high and anthropogenic impacts are often minimal (Brown, 2002, 2005).

II.6 Glacier Studies in Sikkim Himalaya

The cryosphere study in Sikkim, eastern Himalaya, India, has covered mostly the western and north-western part of Sikkim. However, most of the study is based on remote sensing and GIS application because of the fact that in most of the cases this region does not favor the climate and rugged terrains as well. Due to the limitation of field based study in every part - snow cover, mass balance, melt-water discharge and weathering rate, it is always difficult to build relationships between the past and the present study.

Other than the field based study, many studies have been done using remote sensing applications. Few of them focuses mainly in the area of snow cover and river hydrology. The study by Basnett et al. (2011, 2012, 2013, 2019) in the field of snow cover estimation has focused the variation in Snow Cover Area across the Sikkim Himalaya. It has centralized the distribution of snow cover in Teesta and Rangit sub-basin which covers an area of 7096 km^2. This study has been done with the help of multiple satellite imageries-MODIS and AWiFS. The study highlights that as compared to western Himalaya, Sikkim has different snow accumulation and ablation pattern. This region receives the winter precipitation through western disturbances and higher precipitation in summer months helping to provide better inputs for the glaciers of this part of eastern Himalayan region.

Few other studies which has been done in this part of the Himalaya includes the study of snow hydrology in Teesta basin of Sikkim as well as the characteristics of glaciers and snow fed river in these mountainous regions and the glacier morphology. The study by Krishna et al. (1996, 1999, 2005, 2011) and Hazra and Krishna (2017, 2019) highlights that the glaciers depending on their size has an impact on change of areas mostly in medium sized glaciers. The study by Hazra and Krishna (2019) shows that the tributary or branch glaciers are more responsive and rapid changes were observed than in the main glacier body. Some tributary glaciers also showed very low change between the period 2000 and 2018. The above study also highlighted that because of the increase in temperature in these parts of Himalaya, few glaciers namely, Teesta Khangse, Changsang and Zemu, is showing receeding pattern both area and length-wise. It also means that increase in minimum temperature may entail increase in night time warming. The morphometric change of glacier has also been observed because of the changing behavior of climate. The supply of water downstream would have negative impact in future because of the change in atmospheric temperature and amount of snowmelt which can lead to shrinkage of glaciers as well.

The studies related to glaciers and its features in Sikkim Himalaya has emerged at higher pace in recent years in which the northern most part of Sikkim has also been covered widely. Recent studies in this region also highlights the glacial feature of Chopta and Lashar Valleys in north Sikkim to study the detailed geomorphology, its depositional and erosional imprints (Dubey et al., 2017, 2019). The moraine based study is done to understand the extent of area of paleoglacial and their corresponding ice volume during different stages. These studies suggest that glaciers in this region are melting and radically responding to global warming as well as potentially vulnerable to GLOF.

The present work discusses wide range of cryospheric issues and challenges as well as the opportunities in the field of glacier studies. However, it has limitations in Himalayan regions because of inaccessibility and rugged terrains. The Himalayan regions shows a spacious range of variations in local and regional climatic pattern which makes difference in behavior of glaciers from one part of Himalaya to other. Few glaciers in Karakoram ranges and in western Himalaya shows gain in its mass where most of the glaciers terminus and area are receding in western, central and eastern Himalaya.

The western and central Himalaya has ample number of field and remote sensing based studies whereas the eastern Himalaya was lacking the cryospheric studies due to inaccessible terrains and lack of meteorological data. Remote sensing applications in last few decades have made it possible to study those areas as well which are inaccessible through ground and has provided with full of opportunities. Knowing the importance of glaciers, snow and ice, it is highly imperative to explore these areas. The relationship of glaciers with climatic parameters shows its behavior and contribution in the form of melt runoff in the river, controlling the seasonal discharge and sediment transportation in a glacierized basin. Scrutinizing the health of glacier on regular basis is of utmost importance in mountainous region as it is the most important indicator of climate change and global warming as well as the availability of water resources for the use of various purposes.

Chapter III

Glacier Geomorphology and Landforms

Glaciers are considered to be one of the effective agents of landscape changes; and landforms in glaciated valleys are the action of glaciers over period of time. Most of glacial landforms were created by movement of large ice mass during the quaternary glaciations followed by de-glaciation (Berger et al., 1993; Fredin et al., 2013). Glaciers and the associated landforms are considered as the direct and best proxy data archive as well as receptacle of environmental change indicators (Clark et al., 2012). Formation of glacial landforms in the Himalaya needs a nuanced understanding as it addresses a number of process domains at varied time scales and magnitudes to represent changing environmental conditions. At the time of evolution, landforms contained past climatic condition signatures, which helps in understanding the environmental change as a whole and change in glacial features (Owen et al., 2005; Owen, 2009; Pearce et al., 2017; Shukla et al., 2018).

The Himalayan region with amazing geomorphologic diversities also offers a rich field for the study of glacial and periglacial, tectonic, glacio-fluvial and fluvial landscapes (Dutta 2017; Sharma et al., 2018). Active glaciers and associated landscapes provide an ideal platform for better perspective of glacial, fluvial and slope processes; however, limited study has been carried out on the nature of landform evolution in the mountains due to rugged topography and inaccessibility of the region. With this assumption, the present study has been carried out in Changme Khangpu basin of the Sikkim Himalaya for understanding of geomorphology, and related processes. Further, the study gives idea of glacial change within the basin focusing on Changme Khangpu Glacier.

III.1 Topography, Climate and Geology

Changme Khangpu basin is rugged with varied assemblage of landforms. The elevation of the basin ranges from 1,540 to 7000 m a.s.l and it occupies an area of

~792 km^2. About 90 % of the basin area lies above 3000 m a.s.l with slopes above 45^o except in the valley bottoms. Total slope area which is above 45^o is around 637.28 km^2 and the slope ranges from 0^o to 89^o. The highest percentage of the basin area is between 79^o to 89^o slope which is around 261.03 km^2 and lowest is 28.05 km^2 under 0^o-9^o slope. Various small water streams originating from the surrounding glaciers of the basin itself join the Lachung *Chhu*, one of the tributaries of river Teesta.

Climate in the Sikkim Himalaya varies from Sub-tropical and temperate to alpine and tundra type (Chakravarty et al., 2012). Sikkim receives maximum rainfall during monsoons, however, some amount of rain happens during post-monsoon as well; while precipitation in the form of snow happens on higher altitude (Krishna, 2005; Basnett et al., 2013). Pre-monsoon rain occurs in April-May and the monsoon normally begins from June and continues up to early October. With the immediate onset of monsoon, the low -pressure zone in the region draws the moisture laden air off the Bay of Bengal. Hence, the Himalayan Belt of Sikkim receives monsoonal rains, which persists for three to four months. The state receives an annual precipitation of 2000 to 4000 mm; of which the annual rainfall varies between 82 mm and 3494 mm. Thangu in North Sikkim receives least rainfall and Gangtok gets the maximum (Sengupta et al., 2009; Singh et al., 2019). Whereas the study area receives an annual rainfall of 2401 mm and areas above 2800 m a.s.l. gets precipitation in the form of snow. The area has summer between June to August, and winter from November to March. Temperature in the study area varies from 9^0 to 25^0 C in summer and -7^0 to 9^0 C in winters. Temperature above the altitude of 3800 meters is polar tundra type which is characterized by cool summer, cold winter and a summer rainfall regime.

Changme Khangpu basin lies in the higher Himalayan crystalline, which is bounded by the Main Central Thrust in the south and the South Tibetan Detachment System in the north (GSI, 2011). The basin has a large area in the north under permafrost conditions and is yet to be mapped for landforms formations. Southern part of the basin is much more exposed and is composed of two major lithologies of the Central Crystalline Gneissic Complex (CCGC) i.e. the Chungthang formation and the Kanchenjunga Gneisses. The Central Crystalline Gneissic Complex (CCGC) represents the Precambrian sequence of Sikkim along with the lower grade Daling group of meta- sedimentary rocks that are exposed in the central part of the state (Chakraborty et al., 2016). The Chungthang Formation rocks are composed of quartzites, garnet-kyanite-staurolite bearing biotite schist, calc silicate rock, graphitic schist and amphibolites and are exposed in the area as large patches (Acharyya, 1989). Major rock formation in the region is Kanchenjunga Gneiss. It is bounded by the Tethyan sequences in the north and is composed mainly of banded /streaky gneisses and migmatites, augen bearing gneisses and granite gneisses. These are characterized by frequent interchanging among themselves. Kanchenjunga Formation in this region is majorly composed of banded gneiss characterized by rich alternating bands of Quartzo-feldspatic material and mafic schistose materials. Interspersed among the Kanchenjunga gneisses small outcrops of basic intrusive have been reported (GSI, 2012).

III.2 Altitudinal Zonation of the Basin

The basin was divided into five zones primarily on the basis of altitude, vegetation, climate types (Table III.1). Relief of the basin is moderately high and the altitude of the Changme basin ranges from 1541 to 7000 m a.s.l. Lower part of the basin has settlements stretching up to the 3000 m a.s.l.

III.2.1 Zone I (1500-2500 m a.s.l)

As seen from the table no. III.1, Zone I occupy only about 2.3 % of the total basin area and comprises of 17.69 km^2. This zone has settlements right from Chungthang and above. Annual average temperature of this area is around 16^0 C. It is zone of sub-temperate climate and hard wood trees are prevalent with high amount of lichens, mosses and ferns.

Table III.1: Altitude-wise distribution of total area of the Changme Khangpu Basin

Altitude (m a.s.l)	**Area** (km^2**)**	**Area (%)**
Zone I (1500-2500)	17.69	2.29
Zone II (2500-3500)	78.41	10.18
Zone III (3500-4500)	198.68	25.80
Zone IV (4500-5500)	415.78	53.99
Zone V (5500-6500)	57.33	7.44
Zone VI (6500-7500)	2.08	0.27

III.2.2 Zone II (2500-3500 m a.s.l)

The zone II comprises of 10.18 % of the total area (78.41 km^2) where the annual average temperature is around 9^0 C. This zone has temperate type of climate and has broad leaved hard wood trees and coniferous forests. The area gets longer winter where annual precipitation is moderate to high going up to around 1094 mm. Fluvial and glacio-fluvial processes dominates this zone and human settlements are confined up to the maximum altitude of 3000 meters covering all the permanent villages of Lachung as well as temporary settlements above it (Fig. III.1 and Table III.2).

Table III.2: Altitudinal Zonation of Changme Khangpu Basin

Zones and Classification	**Altitude (m a.s.l)**	**Mean Annual Temperature (°C)**	**Annual Rainfall (mm)**	**Climatic Zone & Climatic Type**	**Vegetation**
I (Warm and Sub-Temperate zone)	1500-2500	16.0	2401	Sub-Temperate Zones (Cwb)	Mix vegetations& temperate broad-leaved forests
II (Warm and Temperate)	2500-3500	9.4	1094	Temperate Zone	Coniferous temperate forest&

				(Cwb)	broad leaved
III (Sub-Alpine)	3500-4500	-3.75*	58.09*	Alpine Zone (Cwb)	Pine fir, alpine moist forest and alpine pasture's
IV (Tundra climate)	4500-5500	-0.1	347	Glacier Zone (ET)	Shrubs, alpine meadows and alpine scrubs
V (Cold desert)	Above 5500	Frozen	Snowfall	Frozen Zone (ET)	No vegetation

*__Note:__ Average annual temperature in the year 2018 (climate type symbol is based on Koppen's Climatic Classification)

III.2.3 Zone III (3500-4500 m)

This zone is the transition zone from Temperate to Sub-alpine and alpine zone, and comprises of 25.80 % (198.68 km^2). Cone bearing needle leaved trees, dwarf alpine firs, silver fir and alpine pastures are dominating vegetations in this part of the basin. The landscapes in this zone are mostly aretes, U-shaped valleys and valley steps.

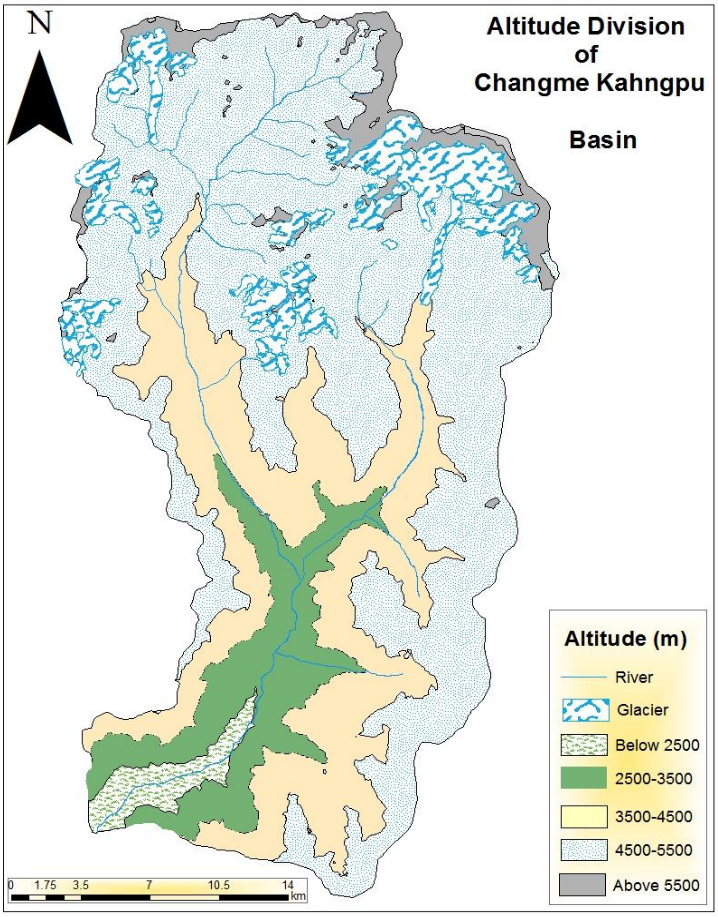
III.2.4 Zone IV (4500-5500 m)

The percentage share of this zone is highest around 53.99 % (415.78 km^2) of the total basin area. Annual temperature and average precipitation of this zone is around -0.1 ^{o}C and 347 mm. This zone falls into Tundra type of climate which is characterized as glaciated zone. The vegetation is mainly dominated by shrubs, bushes, alpine meadows and alpine scrubs. Glacial and glacio-fluvial processes are active in this area. Many glaciers also have ablation area in this zone, and landforms like moraines, outwash plains and other fluvial processes are also active in this zone.

III.2.5 Zone V (Above 5500 m)

This zone covers 7.71 % of the total basin area (59.41 km^2) and are with almost no vegetation. The zone is characterized as frozen zone or glacierized area (snow/ice-covered throughout the year), mainly the accumulation zones. Landforms like cirques, bergschrund, hanging glaciers and ice falls dominates in this area (Fig. III.1).

Fig. III.1: Altitudinal zonation of the Changme Khangpu basin



III.3 Inventory and Mapping of Glaciers

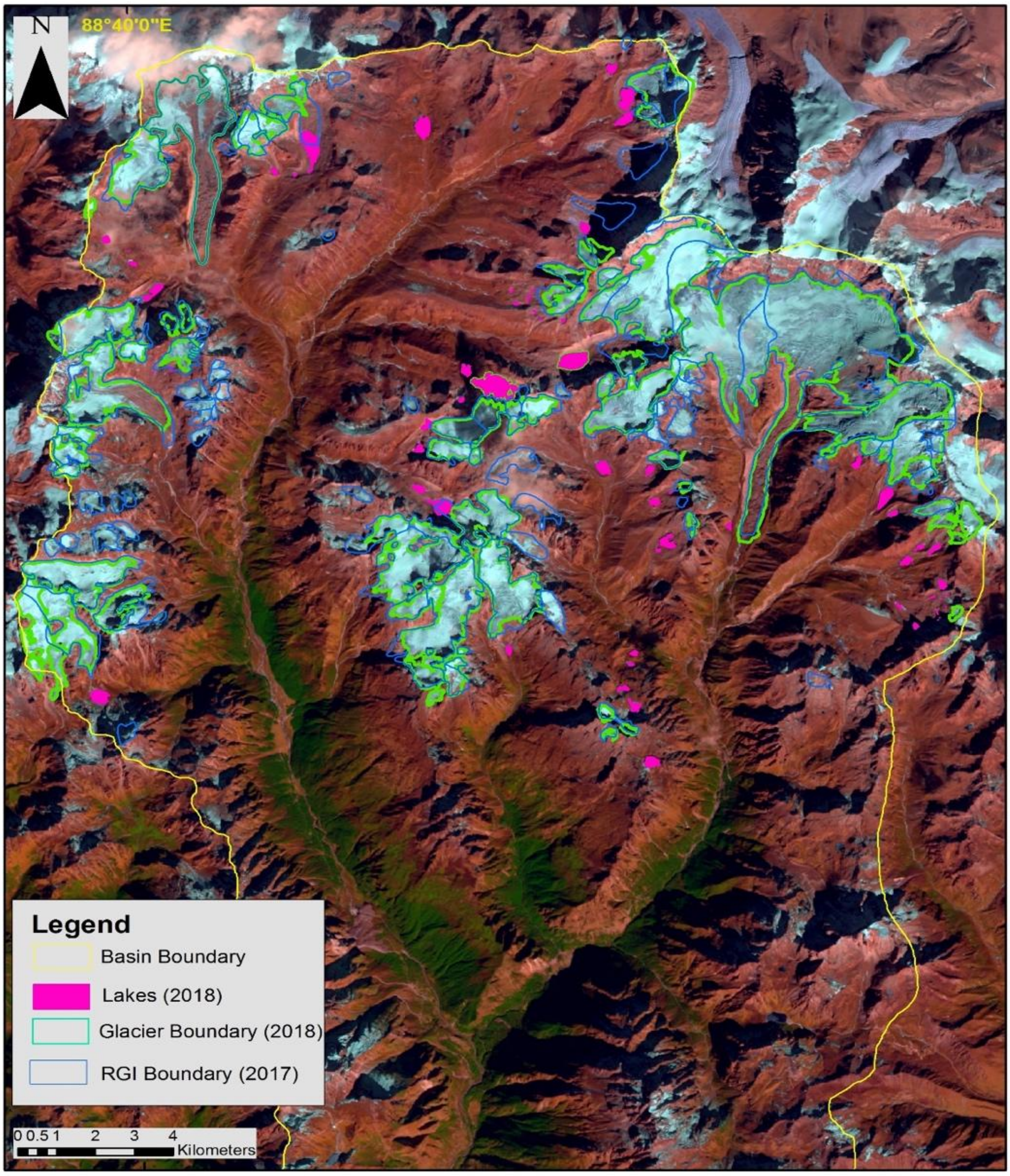
The inventory of glaciers in Changme basin of North Sikkim has been done to assess the distribution and areal extent of glaciers in the basin. The glaciers were mapped using the remote sensing method and manual correction of glacier’s boundary. Remote sensing method includes the imageries from declassified Corona images of 1962, Landsat 5, 7 and 8, Sentinel-2 images of 2018 and named using topographical sheets acquired from Department of Science and Technology, and the Department of Mines, Minerals and Geology, Government of Sikkim. First, the glacier outlines were extracted using semi-automated method in Arc GIS 10.2 using band ratio approach, applying suitable threshold to differentiate between water and Ice/Snow pixels and other conditional parameters/filters like extracting water, vegetation, cloud filters and also RGI boundary of 2017. The glacier outline was then manually corrected using IRS-LISS-III image 2005, Landsat7 ETM+ of 2005 of 15-meter resolution and Sentinel-2A&B MSIL1C image of 2018 having resolution of 10 meters (Fig. III.2). On the basis of Survey of India maps of 1:50000 scale and satellite imageries, a total of 58 glaciers were identified and mapped in the Changme Khangpu basin. Out of these 58 glaciers, 14 glaciers have distinct names in the topographical sheet (1960) and rest has been given numerical ID's on the basis of mapping.

This study shows that the larger glaciers are fragmented into smaller glaciers (tributaries) which increased the total number but resulted in decrease in areal extent of glaciers. Total number of glaciers identified in 2018 in the Changme Khangpu basin are ~58 with the 120 glacial lakes. Total glacier area is 70.68 km^2, whereas the lakes cover an area of 4.83 km^2. Increase in number of the glacial lakes and its area may possess threat of GLOFs in the region in near future. This study provides an overview of 24 selected glaciers for change analysis in glacier areal extent from 2005 to 2018. Total area occupied by these glaciers in 2005 was 78.36 km^2 and in 2018 the area was ~65.77 km^2.

According to the study of Randolph Glacier Inventory (RGI), the number of glaciers in Changme Khangpu basin is 88 occupying a total area of around 86.98 km^2. The difference in areal extent of this study and RGI for exactly 58 glaciers' is around 3.16 km^2. This study presents 58 glaciers having an areal extent of 70.68 km^2 in 2018 as compared to the RGI marked in 2017 having an area of 73.84 km^2. Fig. III.2 gives an overview of RGI glacier boundaries with the present study boundaries.

The glacier inventory has been prepared and it defines the following parameters namely- name/ID of the glacier, its latitude and longitude, area (km^2), length (m), altitude highest (m), altitude lowest (m), orientation of accumulation, orientation of ablation (Table III.3).

Fig III.2: Changme Khangpu basin boundary overlaying on Landsat 8 OLI imagery of December 2018.



Glacier name/ID: Name of the glacier is given in the data base for those glaciers, which are there on the topographic map. Numeric values have been used in the map where name was not found.

Latitude and Longitude: Latitude and Longitude of the glacier is in the degree decimels.

Length of the glacier: Length of the glacier is measured from the tongue to the head of the glacier.

Orientation of the glacier: the orientation of accumulation and ablation area is represented in eight cardinal directions (N, NE, E, SE, S, SW, W, and NW). The orientations of both the areas (accumulation and ablation) are the same for most glaciers.

Elevation of the glacier: glacier elevation is divided into highest elevation (the highest elevation of the crown of the glacier), and the lowest elevation.

Table III.3: Glacier properties and change in areal extents of glaciers in Changme Khangpu Basin

Name/ ID	Longitude	Latitude	Area-2005 (km^2)	Length (km)	Altitude		Average Altitude	Orientation Accumulation	Orientation Ablation	Area-2018 (km^2)
					Maximum	Minimum				
Yulhe Khangse	88.6589	27.9699	2.17	2.14	6200	5000	5600	N	SW	1.17
Tista Khangse	88.8211	27.9487	8.2	6.14	6800	5350	6075	SN	SN	6.5
Tenbawa Khangse	88.8043	27.9202	6.59	4.33	6100	5300	5700	NS	NS	5.7
Rulak Khangse	88.6614	27.8932	3.85	3.15	5600	4800	5200	WE	ES	2.87
Lako Khangse	88.7392	27.849	3.8	3	5650	4800	5225	NS	NS	3.26
Kangpup Khangse	88.7572	27.8608	1.77	1.97	5600	5100	5350	EW	EW	1.66
Khangkyong Khangse	88.8409	27.8988	23.31	8.38	6100	4450	5275	NS	SW	22.54
Changme Khang	88.6681	27.9522	2.46	2.48	5500	5200	5350	N	SW	1.83
Changme Khangpu	88.6839	27.96	5.45	5.52	5800	4800	5300	NS	NS	4.84
Toklung Glacier	88.7634	27.842	2.74	295	5600	4700	5150	NS	NS	2.24
Sebu	88.6561	27.9113	2.11	2.2	5700	5050	5375	SW	NE	1.94
Burum Khangse	88.649	27.8335	2.07	3	5500	4800	5150	NS	NS	1.36
Burum Khangse1	88.642	27.8311	1.82	3.89	5600	4800	5200	NS	NS	1.17
Burum Khangse2	88.6527	27.847	2.53	3.13	5400	5000	5200	WE	WE	2.02
9	88.6644	27.8401	1.35	2.08	5400	4600	5000	WE	WE	0.77

15	88.6346	27.8842	0.85	1.93	5800	5200	5500	NS	NS	0.59
20	88.7526	27.8837	0.86	1.43	5600	5400	5500	EW	EW	0.51
22	88.8682	27.8752	2.4	1.81	5900	4800	5350	NW	SW	1.69
21	88.8756	27.8615	0.43	1.2	5500	5000	5250	E	E	0.46
33	88.7658	27.8745	0.95	1.44	5400	5150	5275	E	WS	0.72
34	88.6784	27.9027	0.92	1.08	5550	5050	5300	Open	Open	0.28
35	88.6414	27.8818	0.8	1.97	5900	5000	5450	NS	NS	0.3
44	88.6891	27.8992	0.31	0.53	5500	5200	5350	WE	WE	0.41
55	88.7759	27.836	0.62	1.44	5350	5000	5175	WS	WS	0.56

The ELA has also been identified and marked for the benchmark glacier between year 1962 and 2018. Shift in ELA of the benchmark glacier Changme Khangpu also shows melting of the glacier (Fig. III.3). The ELA in 1962 stood at 5000 m a.s.l while in 2018, it was marked at an altitude of around 5295 m a.s.l. Further, seven glaciers including Changme Khangpu were selected for changes in areal extent between 1962 and 2018. Overall, the glaciers in the basin has decreased in its area from 0.5 km^2 to 1 km^2 (Table III.3).

Fig III.3: (a) Blue and red color shows the Equilibrium line Altitude in the year 1962 and 2018 **(b)** pictorial view of the accumulation zone (photo: September, 2016).

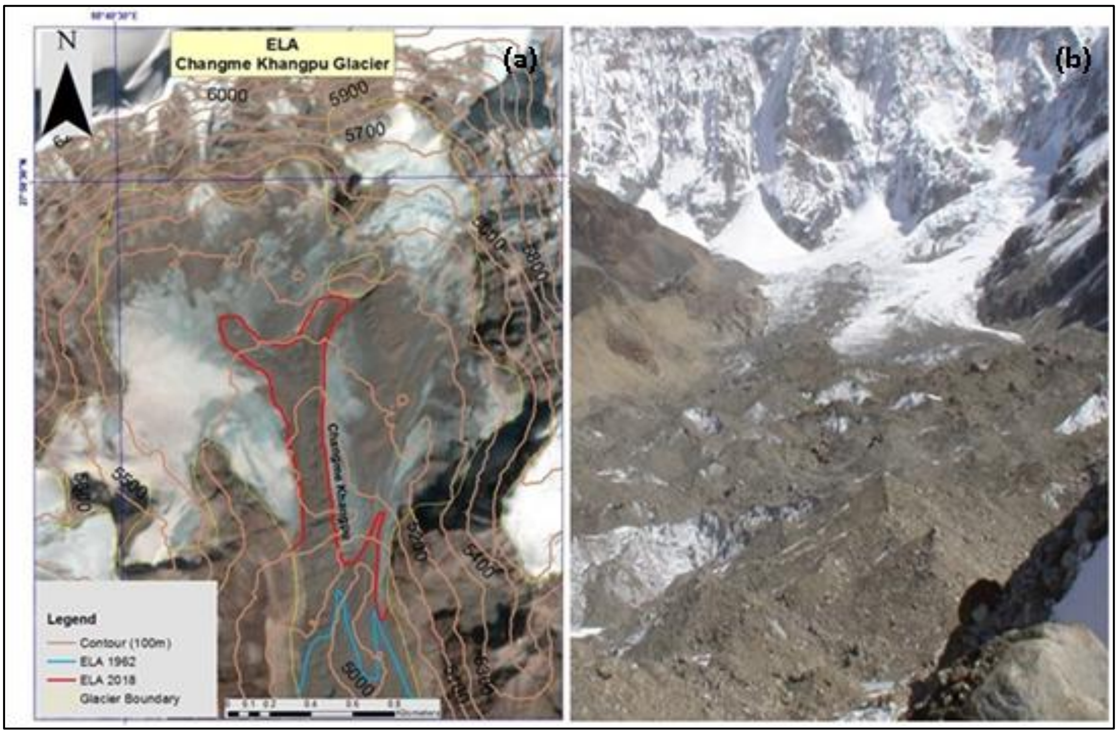


Table III.4: Areal extent of the glaciers in CKB between 1962 to 2018.

ID/ No.	Glacier Name	Area (km^2) 1962	Area (km^2) 2018	Change (km^2)
1	Changme Khangpu	5.65	4.84	0.81
2	Changme Khang	2.81	1.83	0.98
3		1.06	0.84	0.22
4	Palo Chuthang	1.19	a) 0.48	0.54
			b) 0.17	-
5	5*	0.58	-	-
6	6*	2.06	1.84	0.22
7	Chombu	2.18	1.94	0.24
8	Illibu Khangse	1.86	0.81	1.06

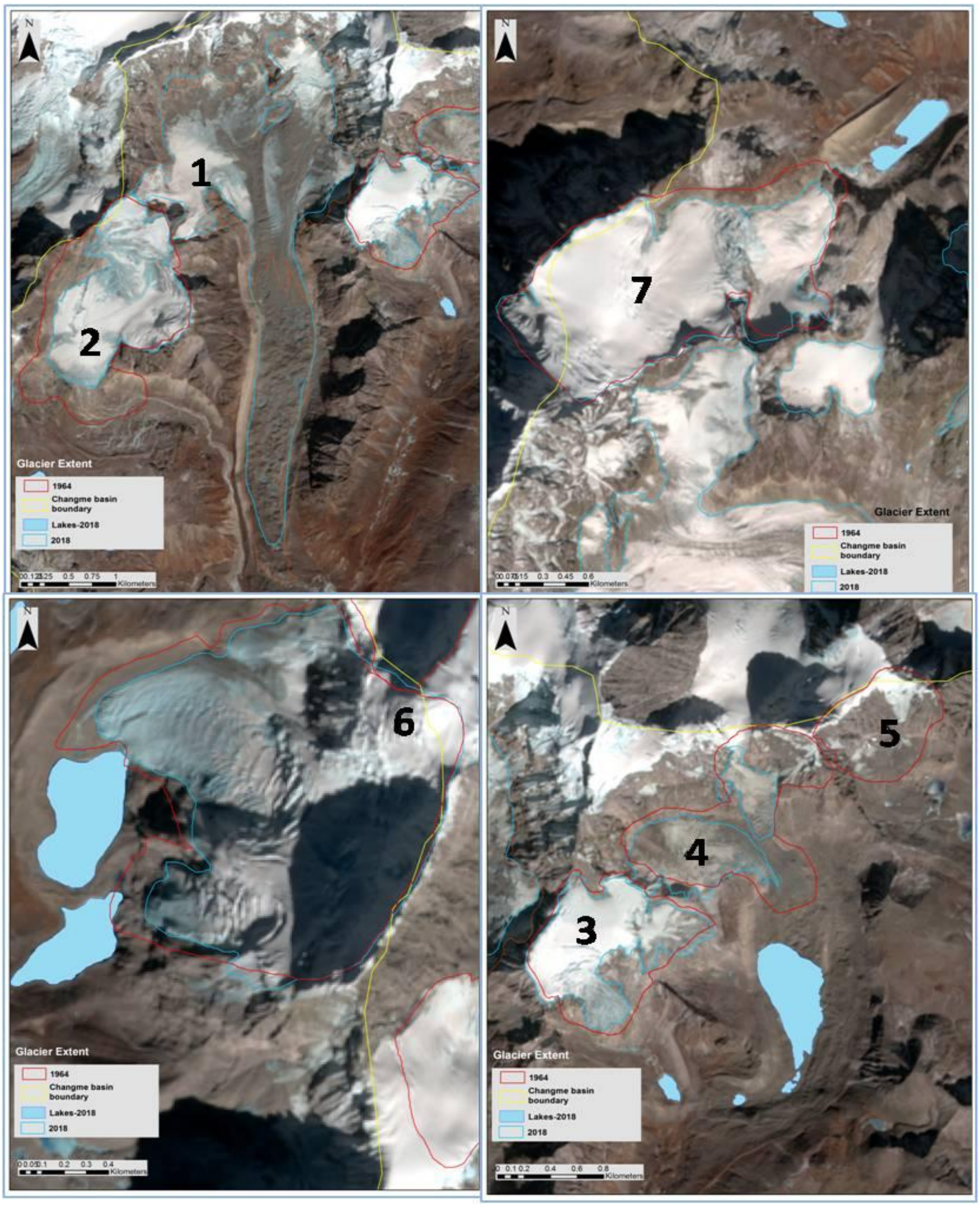
(*numbers/glacier ID's has been used where the name for the glaciers are not known)

Glaciers marked in the Changme Khangpu basin have an area of 70.68 km^2 against the total basin area of 792.17 km^2. Major change noticed is in the area of Illubu Khangse Glacier which has decreased around 1.06 km^2 between 1962 and 2018 (Table III.4). Glacier (ID 5) having an area 0.58 km^2 in 1962 has almost disappeared in the 2018 imagery. The Changme Khangpu Glacier also shows a decrease of area by 0.81 km^2. The area of Palo Chuthang Glacier was around 1.19 km^2 in 1962 which has decreased by 0.54 km^2 of area in 2018 and has split into two small glaciers from a single glacier (glacier ID 4, Table III.4, Fig. III.4).

III.4 Geomorphology of Changme Khangpu Basin

Glacial geomorphology can be used to explain the impact of glaciers on landforms and landscape development (Gillespie, 2011; Glasser et al., 2008; Lardeux et al., 2016). They are also known as the key indicating features for the study of glacial stages and past glacial extensions (Owen et al., 1997; Dobhal and Mehta, 2010; Harrison et al., 2019). Old glacial moraine ridges, terminal moraines and paleo-lakes are few of the direct evidences for the study of paleo-glaciations in the Himalaya (Dhar et al., 2010; Scherler et al., 2010).

Fig. III.4: Glacier boundary- 1962-2018 mapped from Corona Declassified satellite images and Sentinel-2 December 2018.



Two sets of map has been prepared for the understanding of geomorphology of the area- (a) the first set gives the idea of all the features and landscapes in the basin as a whole (Fig. III.5) and (b) the second set gives the closer view of geomorphic features of the area in the form of three sub-figures focusing on each side of the basin in a more closer way (Fig. III.6a, b, c). Detailed mapping was done through manual digitization of various landforms and features in Arc GIS 10.2, with Google Earth Pro images and using field information. The drainage were extracted manually as well as using hydrology tools both to minimize the mapping error as much as possible. Landforms studied and recognized in the basin are results of three to four stages of glaciers and several well developed erosional and depositional, glacial and periglacial features. Series of lateral, medial and end moraines are identified above the Yumesamdong base camp (4700 m a.s.l). Crests of the lateral moraines are tens of meters higher than the present glacier ice surface.

The various landforms observed are classified on the basis of topographic and physiographic distribution of the area and different glacial processes. Glacial troughs or ‘U-shaped’ valleys have been identified near the base camp (4700 m a.s.l) and also at an altitude of around 3800 meters. The other depositional features are terminal, medial and lateral moraines, lacustrine deposits, talus cones and snow avalanche fans, glacial terraces, debris and glacial boulders or erratic fields, rock cliffs (break of slopes), ridge and crevasses, supra-glacial ponds etc. Rock glaciers exist above 4000 m a.s.l and they are typically characterized by large clasts and crude down-slope stratification. An extensive outwash debris complex is present from the lateral moraine of some glaciers and is also characterized by large clasts as well.

Presence of aretes and horns in lower part of the basin indicates that the basin had glacier's in the lower altitudes possibly during the little ice age (Fig. III.6c) (Bacon et al., 2001). Entire Lachung valley was glacial valley and presence of high ridges and deposition of moraines in lower parts are the indicator of glaciations in the past. Yumthang valley was initially formed by erosion due to glacier and later followed by erosion due to river giving it a shape of U-shaped valley having moraines and avalanche paths provides an evidence of last glaciation period.

Fig. III.5: Geomorphic features of the Changme Khangpu basin identified using Google Earth Pro, Landsat 8 image of 2018, Sentinel-2, 2018and field visits from 2015 to 2017.

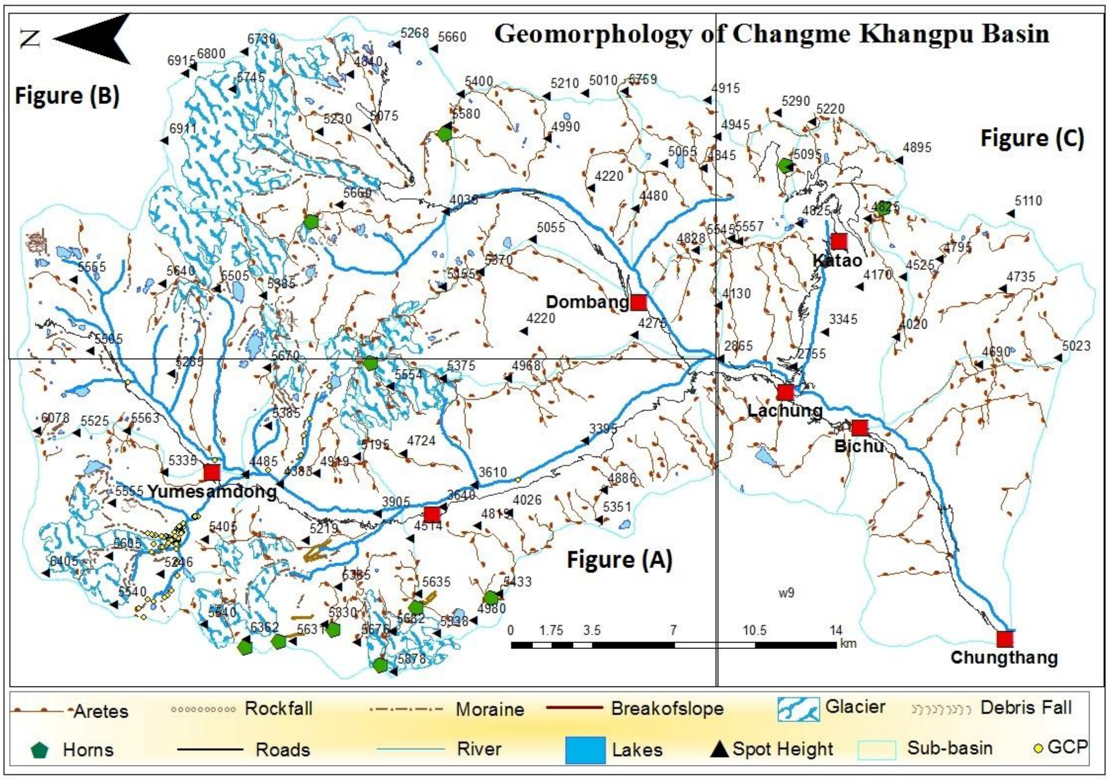
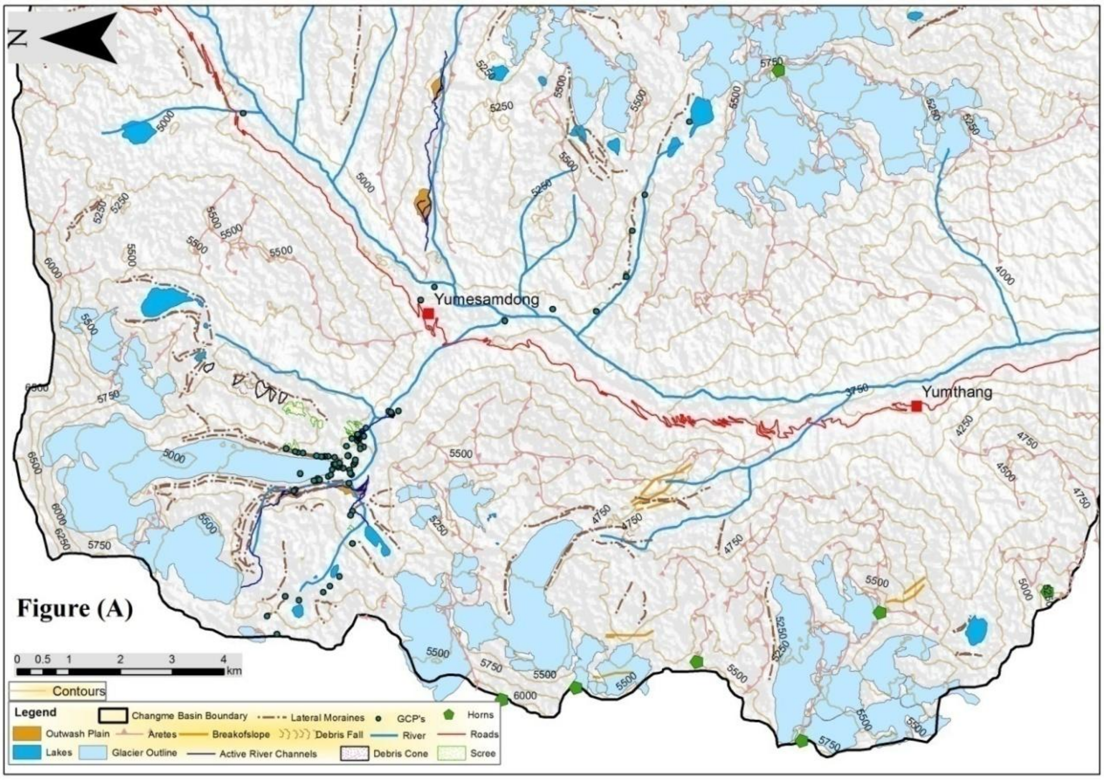
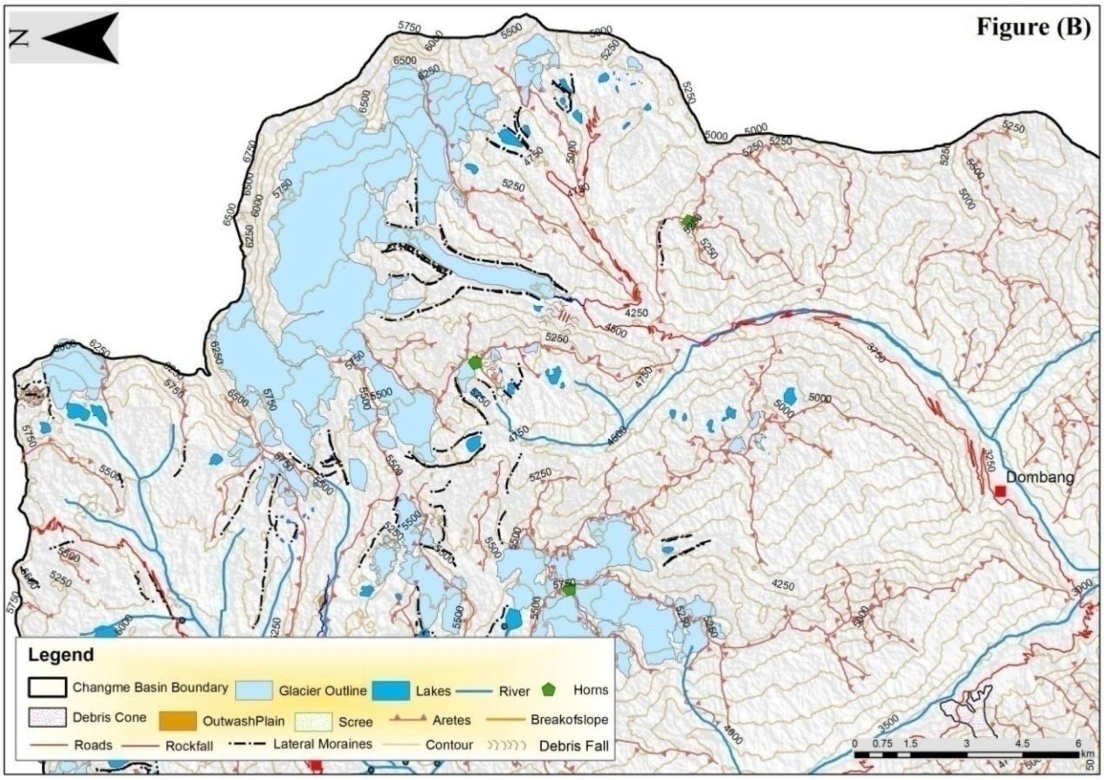
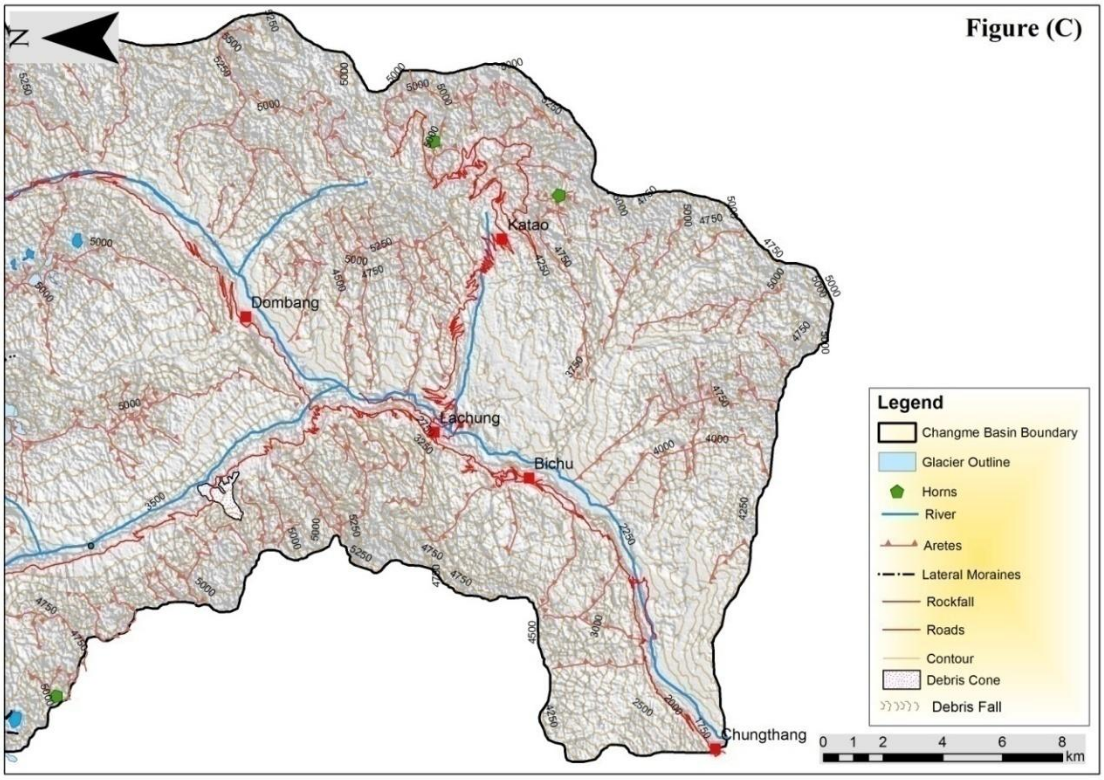


Fig. III.6: Sub-division of Fig. (III.5) named as (A), (B) and (C) for a closer view of the valley. The basin boundary and the features are overlaid on the hill shade relief of the basin with contours at the interval of 250 m.







Upper part of the basin, above altitude of 4000 meters is full of glaciers, supra glacial ponds and glacial lakes (Fig. III.3A, B). Large terminal and lateral moraines marked in the field are evidences of extent of glaciers in the region. It indicates the existence of glacier's for longer period in some stage in the past. Part of the basin is also dominated by moraine dammed lakes and small supra-glacial ponds in the ablation zone of the glacier which is increasing in its size and hence, the risk of GLOF's. Outwash plains are also one of the landscape features observed in the upper part having fine and thick sediment deposits transported by glaciers near its terminus area. In the lower part of the basin, below 4000 m a.s.l is well developed U-shaped valley formed by glacio-fluvial processes. Part of the basin has well developed fluvial valleys and have dendritic drainage pattern. It is also dominated by landslides and slope failures as well as avalanches in the valley bottoms. Landscape modification due to glacial and glacio-fluvial actions are frequent in the basin and will continue in future in form of mass movements and glacial/ periglacial/ pro-glacial activities.

III.5 Glacier Characteristics and Landforms

This part of the eastern Himalaya is predominantly influenced by the Indian summer monsoon implying that it receives precipitation mainly during summer. Most of the glaciers are valley type. Accumulation over the glacier occurs through both direct snowfall and snow avalanching. These valley type glaciers are longer in length where lower reaches are covered with thick supra-glacial debris cover. Continuous and intensive cryogenic weathering of bed rock and gravitational processes are responsible for production of large quantities of sediment above the glacier ice margins in this region, which finally gets incorporated into ice. Avalanche, sliding of ice and debris from steep rock is common in the upper as well as lower parts of the study area. Different types of landforms have been examined in detail to associate these with landform processes and environment. Glaciers in the Himalaya, due to high sediment yields and high-relief mountain environment, contain valley floors that are commonly filled by very large volumes of sediment, and in tectonically active ranges such as the Andes (Owen and Derbyshire, 1988, 1989). Valley floor in such setting, typically has an extensive cover of supra-glacial debris; sedimentation around glacier margins forms large lateral-frontal dump moraines. Thick supra-glacial and ice marginal sediment of valley glaciers in high relief terrain largely mask sub glacial landform and sediments, so that the former bed of such glaciers are rarely preserved in the geomorphological record.

The basin's glaciers consist of extensive mantles of supra-glacial debris on their ablation zones. Amount of debris on glacier surfaces is controlled by a number of factors; the most important of which is distribution of steep slopes in the glacier catchment. From it, avalanches can deliver rock debris, either from bedrock or pre-existing glacial and paraglacial sediments (Pratap et al., 2015; Benn et al., 2012). Other factors influencing debris cover includes; precipitation which governs the amount of snowfall relative to rock inputs, and hence, the debris concentration in the ice; glacier size i.e. long valley glaciers are most likely to have extensive debris mantles; and bedrock erodibility i.e. resistant, massive rocks such as granite will yield much less debris than highly fractured schists and sedimentary rocks.

Altogether there are 84 glaciers in Teesta basin covering an area of 440.30 km^2 and 251.22 km^2 of permanent snow field (Bahuguna et al., 2001 & Basnett et al., 2013). Lower reaches of many glaciers in the basin is covered with thick debris and supra-glacial ponds. In this part of the region, glaciers are mainly controlled by topography, precipitation and climate. The glacier in the basin is usually fed by precipitation in the form of snow in the winter month and amount of moisture during summer months. Several river flow in the Changme basin which ultimately joins Lachung *Chhu*, passing through Chungthang river and finally drains into the Teesta, the lifeline of Sikkim. Sliding of ice and debris, rock falls, rock creeps and ice and rock avalanches etc. are common in upper part. Glaciers comprise three processes of formation of landforms through depositional, erosional and glacio-fluvial features in a region. The criteria for identification of various types of landforms are mainly based on the literature listed in Table (III.5).

Fig. III.7: Geomorphic features of the benchmark Changme Khangpu glacier

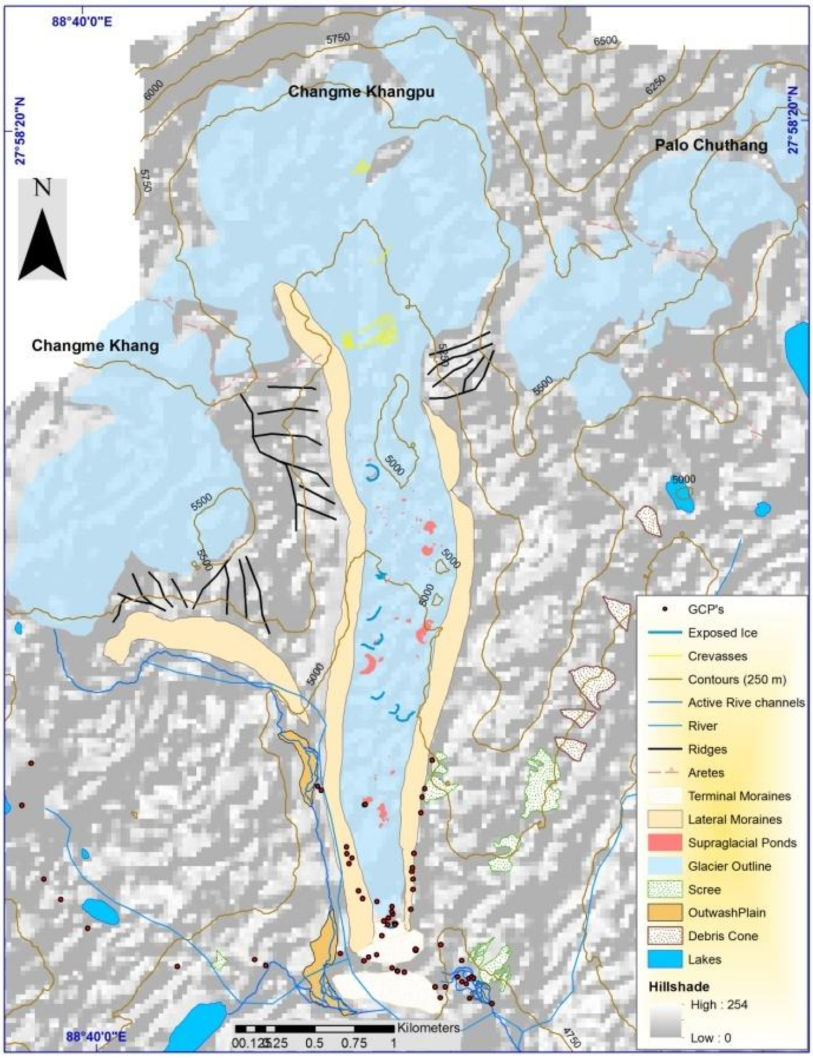


Table III.5: Glacial landforms and their identification on earth surface

Landforms	**Identification Criteria**	**Boundary defined by**	**Significance**
Ice-scoured bedrock	Widespread exposure of bare bedrock with smoothed, striated or plucked upper surfaces	Outermost extent of bare bedrock	Evidence of glacier ice at its pressure-melting point
Drift Limit	The edge of the cover of a glacigenic deposit that is	Outermost extent of glacigenic deposit	Drift limit marks the extent of a glacier

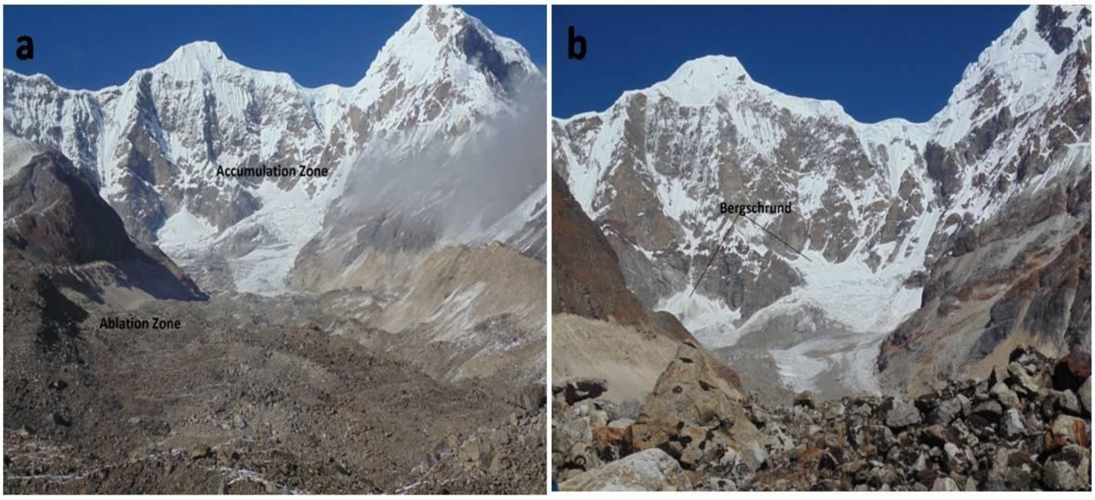
	not also marked by a moraine ridge. Drift limit may be identified by a change in vegetation type or by change in the density of glacially deposited boulders		advance
Moraine Ridge	A single ridge or collection of ridges composed of glacigenic material. Typically, 1-10 m (but exceptionally 100m) in height. Sharps or rounded crests and either linear, curved, sinous or sawtooth in plan	Lower concave break of slope. The crestline orientation can also be recorded if this is well defined	Moraine ridge marks the lateral or terminal extent of a glacier (except in the case of hummocky moraine)
Hummocky moraine	A seemingly chaotic assemblage or irregular hummocks and hollows. Hummocky moraine often shows order when viewed on aerial photograph, or when mapped in detail in the field.	Outermost extent of hummocky moraine. The crestline orientation of individual hummocks can also be recorded if the scale of the map permits.	Formed by the slow melting of stagnant, debris covered ice, by deposition of receding glacier margins, or the release of material from proglacial or englacial thrusts.
Meltwater Channels	Channels cut in rock or sediment, often with abrupt inception and termination and lack of modern catchment. Sub-glacial melt-water channels may breach cols, displaying convex-up long profile	Thalweg of channels, location of channels inception and termination. Arrow to indicate direction of former drainage can also be recorded if known	Evidence of former melt-water discharge routes
Trimline	Line separating areas of solifluction from extensive gulling or areas of mountain top detritus/weathered material from upper limit of ice-scoured bedrock.	Lower limit of solifluction or weathering and upper limit of extensive gulling or ice-scoured bedrock	Former vertical dimensions of a glacier or englacial thermal boundary

Source: (Benn, 1992; Benn and Evan, 1998; Benn and Owen, 2002)

III.5.1 Accumulation and Ablation Zone

Generally, glaciers are divided between two zones (i) accumulation and (ii) ablation which are separated by equilibrium-line altitude (ELA). That part of a glacier where melting occurs is termed as ablation zone and part of the glacier where snowfall accumulates and exceeds the losses from ablation is accumulation zone. Majority of glaciers in Changme basin are either debris covered or hanging glaciers and there is no defined ablation zone for an accurate differentiation of the two zones of a glacier. Lower region of the Changme Khangpu Glacier is fully covered by debris of thickness ranging from 10-60 cm (field observation in 2016-2017, Fig. III.8a, b).

Fig. III.8: (a) Accumulation and Ablation zone of debris covered Changme Khangpu Glacier; **(b)** Closer view of accumulation zone and Bergschrund



III.5.2 Snout of Glacier

Lowest end of a glacier at any given point in time is snout of the glacier. The ice may melt around this point and the melt water produced over the ablation zone percolates, and emerges as a stream at the snout of the glacier (Fig. III.9a).

III.5.3 Crevasses

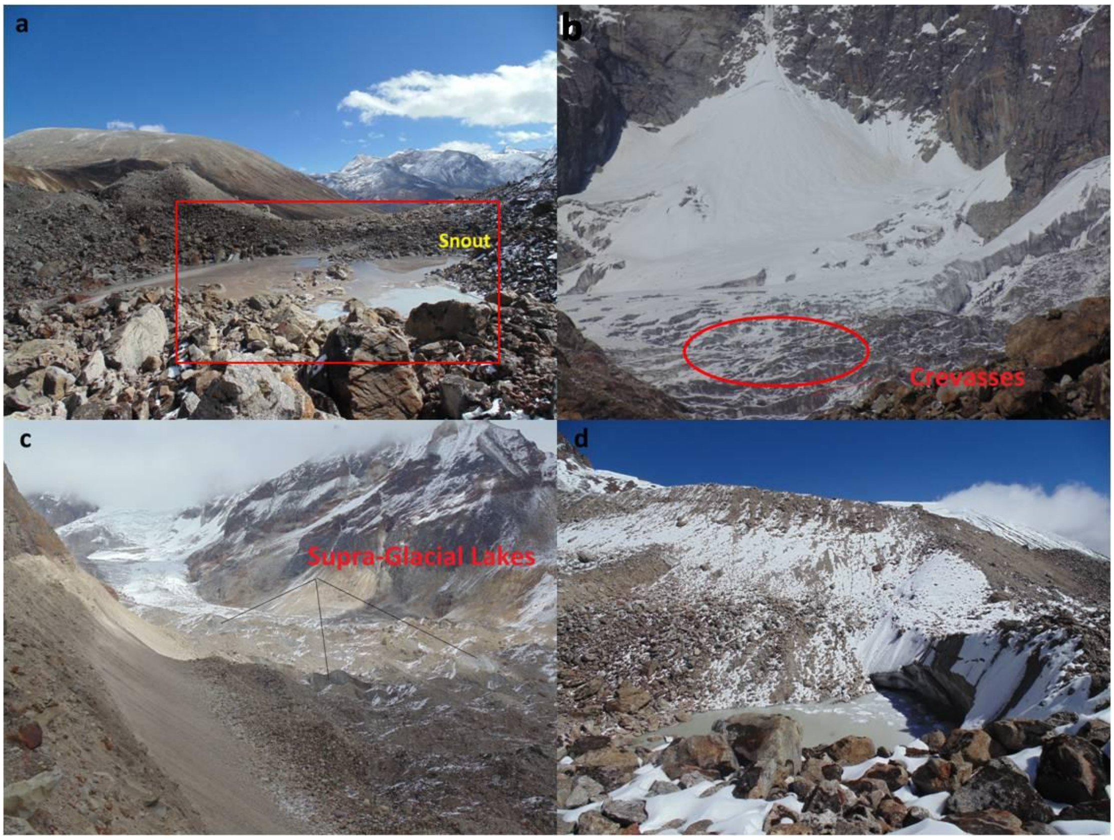
It is most prominent surface feature of glaciers. Crevasses are formed by the deformation of ice as a result of stress generated within the glacier ice. In Changme Khangpu basin, crevasses are mainly developed above the elevation of 4800 meters

(Fig. 9b). These deep open cracks are exposed in summers and are hidden in winter under thick snow cover.

III.5.4 Supra-glacial Lakes

Small seasonal (mainly in summer) lakes formed over the glacier's ablation zone are called supra-glacial lakes/ponds. Although they are ephemeral but they may last for months or even years; these can even get drained out in the course of hours as well. Owing to debris-covered ablation zone prone to higher melting rate, the basin has large number of supra-glacial lakes, especially in the Changme Khangpu Glacier (Fig. III.9c, d). There is possibility of many other lake formations due to enhanced melting, some of which may give rise to a Glacial Lake Outburst Floods (GLOFs) in the near future.

Fig. III.9: Changme Khangpu Glacier's **(a)** Snout **(b)** Crevasses in the ablation area **(c)** Supra-glacial lakes formed over the ablation zone and **(d)** closer view of the lake.



III.5.5 Cirque

Cirques are confined to area of former and present glaciations. Two or three Pleistocene advances of the Himalayan glaciers have been proposed on the basis of cirque level (Krenek and Bhawan, 1945; Vohra, 1981; Mayewaski and Jaschke, 1979). Highest cirque level is recorded from Sikkim (5300-5790 m a.s.l). A deglaciated cirque have also been observed in Changme Khangpu basin below the lateral moraine of Changme Khangpu Glacier (Fig. III.11c).

III.5.6 Moraines

There is a close relationship between the landform orientation and ice flow direction with distribution of moraines in the region. Moraines can also be referred to as archive for studying the environmental change, both locally and regionally. Various type of moraines attributed to the study area are as follows (Fig. III.12).

Lateral moraines

Accumulation of valley side material on either side of glacier are termed as lateral moraines. They are rapidly modified by slope processes in a dynamic environment and so the lateral moraines formed sub glacially can be rare. Several sets of sharp crested lateral moraine ridges are present and are incised in all the places (Fig. III.11a, d). These are present within 3-4 km of the snout of Changme Khangpu Glacier. Older lateral moraine is highest and resembles glacial terraces in the higher parts. Ablation valleys along these lateral moraines are dominated by colluvial sedimentation.

End or Terminal moraines

These features are formed by the movement of glacier snout. Its size and form are related to the volume of sediments contained in the ice, rate of surface ablation and ice movement. End moraines have been observed within 2 km from the glacier in the basin (Fig. III.11a). This also suggests that a large glaciated area has been freed of ice in the valley because of large glacier retreat. The landforms often get rearranged due to glacio-fluvial and slope processes, by action of rapid erosion and re-sedimentation in the basin area.

Medial moraine

It is a ridge of moraine that runs down from the center of a valley floor and the debris of adjacent valley side joins to form between the convene of two glaciers. It is combination of two lateral moraines of two adjacent glaciers.

III.5.7 Glacial Trough

Prevalently known as 'V-shaped' valley, is the channels of present or former glacier or ice streams. Like river, glaciers obey the necessary geometric relationship:

$Q=Av\text{-}=wdv$. Discharge equals mean velocity time cross-sectional area; the latter is approximately with time depth. Ice discharge increases downstream to the equilibrium line and declines thereafter through the ablation zone. Channel cross-sections are roughly parabolic, 'U' shaped, which may develop through erosion, proportional to basal ice velocity or a power thereof (Benn and Evan, 1998). U-shaped valley is the channel of present or former glacier or ice streams. The base camp, Yumesamdong is a deglaciated U-shaped valley of Changme Khangpu Glacier (Fig. III.11b). Because of the importance of basal ice velocity, high discharge of warm-based ice is most effective in eroding trough.

III.5.8 Outwash Plain

These are braided stream flowing from the front end of a glacier. With the continuous flow the glacier grinds the underlying rock surface and carries the debris along. Glacial sediments deposited by melt-water at the terminus of a glacier forms outwash plains which have layers of sand and other fine sediments (Fig. III.12d).

III.5.9 Hanging Glaciers

These are isolated masses of glacial ice flowing high and originates high on the wall of a glacial valley. Only a part of it descends to the surface of the main glacier and abruptly stops at a cliff. Ice and snow transfer to the valley floor below through these glaciers are avalanches and icefalls. The study area has many hanging glaciers and avalanches are a common phenomenon associated with these glaciers (Fig. III.12a).

Fig. III.10: Parabolic valley at Yumthang initially formed by erosion due to glacier followed by erosion due to river.

Fig. III.11: (a) Lateral and End moraines in the basin **(b)** U-Shaped Valley **(c)** Cirque and **(d)** series of moraines in the area above Yumesamdong with outwash plain

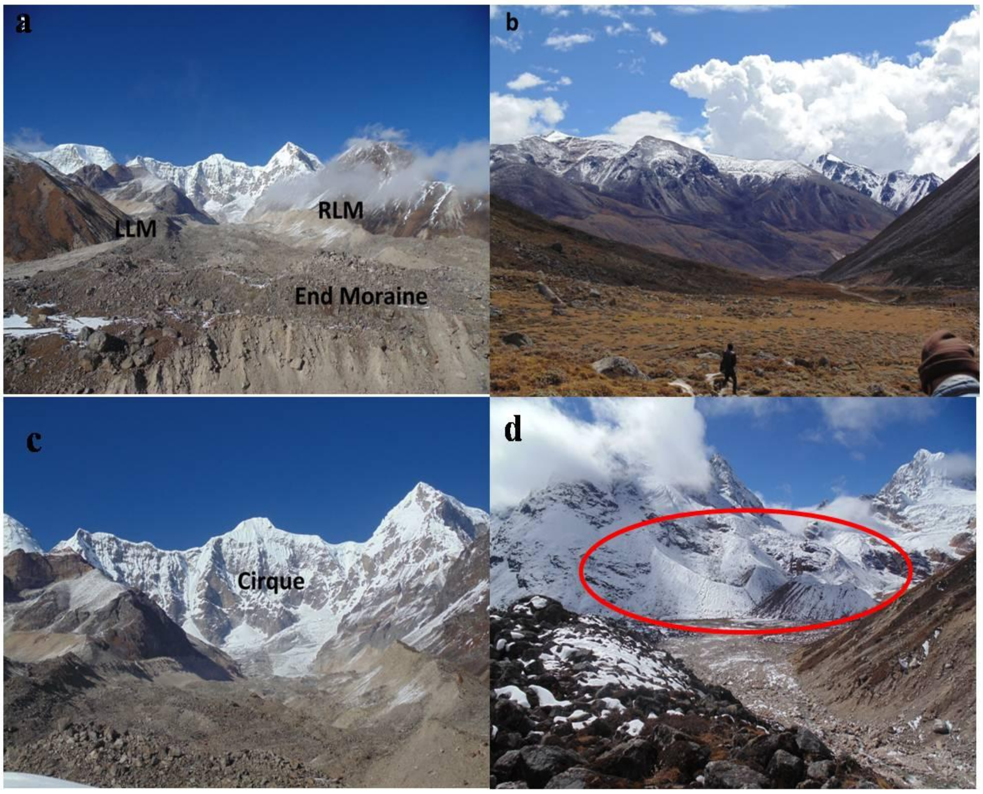
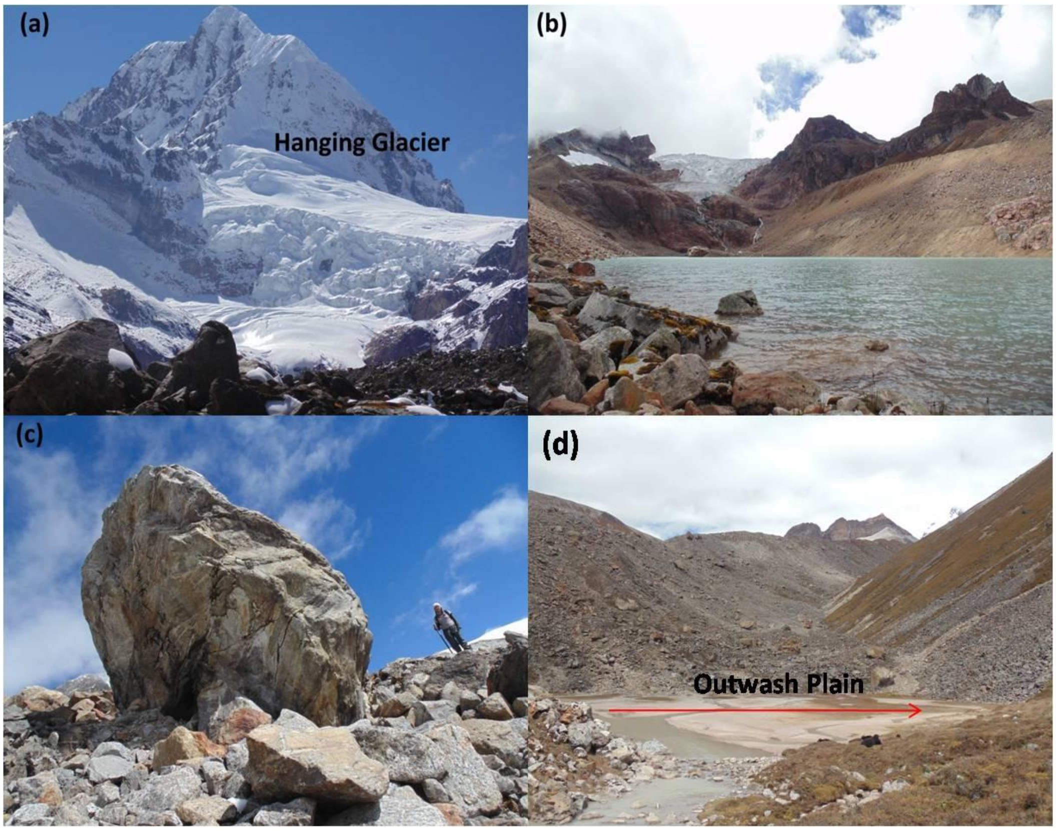


Fig. III.12: (a) Hanging glacier (b) Hanging glacier above Sebu *Chhu* lake (c) Erratic boulders and (d) Outwash plain above Yumesamdong in the Changme basin.



III.5.10 Erratic boulders: is a boulder that has been eroded and transported by glacier to a different area. These boulders differ in size and shape of the native rocks. It can be carried often over distances of tens of kilometers and may be embedded in till or occur at the ground surface because of which it often gives the distance of transport and direction of ice movement. Erratics are composed of unusual rock types and can serve as indicator of important of mineral deposits (Fig. III.12c).

III.5.11 Frost Heaving: is a form of frost action and is continuous physical weathering process which takes place due the cycle of freezing and thawing of water in soil or rock. Frost heave is dependent on three things- freezing temperature, soil and the water supply. Heaving refers to the upward movement of ground surface that occurs in response to the seasonal formation of ice in the underlying soil and the process has been noticed in the basin (Fig. III.13).

III.5.12 Melt-water streams: glacier retreat and melt leads to change in pattern of discharge of water, sediment supply and base-level controls of channel pattern during deglaciation (Marren and Toomath, 2014). The streams in the CKB basin are mostly typical form of braided channels in the upper part. Due to debris cover ablation areas many streams come out from the latero-frontal moraines and emerges out after distance of 300-400 meters (Fig. III.14a). Ox-bow lakes can also be seen in the basin below altitude of 4000 meters and are fast flowing melt water channels from all surroundings in the form of small channels to the tributary which ultimately contributes to the Lachung *Chhu*.

III.5.13 Rock Glaciers: are common in high alpine periglacial or glacial areas. They are result of mountain permafrost and grow due to spring discharge, precipitation and local runoff as well as avalanches. The study area has presence of few rock glaciers. Ice is usually found in the upper reaches of this type of glacier. Rock glaciers are present above 4000 m a.s.l. These rock glaciers are characterized by beheading of glacier ice at the backwall. Glacier ice surface in the lower surface is extensively covered with debris and have extremely slow flow rates (Stenni et al., 2007; Falaschi et al., 2015; Selley et al., 2018). This shows crude down-slope stratification and strong clast fabric. These rock glaciers in upper altitudinal regions may indicate a shift towards more arid climate in the region. The beheading of rock glacier from backwall reflects a decrease in the supply of moisture.

III.5.14 Earth Hummocks: are the assemblage of little cryogenic mounds and are formed in seasonally frozen grounds in periglacial environments. It usually differs in shape from dome to circular or oval. They are located in proglacial area and are developed in fine grained to stone free soils of glacial valley. Distance between the hummocks is in meter or less and in the study area it ranges between 30 cm or less (Fig. III.13).

III.5.15 Gully Formation:

Gullies are typically the landforms found on steep slopes and contains large amount of water ice. Lateral moraines in the basin are incised by numerous closely spaced gullies and the slope angle are up to 70 degrees or more. In glaciated catchments, gullies often expand through recently deglaciated and un-channelized surfaces (O'Connor, 2001; Lancaster, 2012). Snow/frost deposition, their entrapment and preservation results in the formation of gullies on the moraines with sufficient snow and ice accumulation, as it melts it also fills the debris covered glaciers with more debris on the glacier tongue. These are usually called snow gullies (Fig. III.14c).

III.6 Glacio-fluvial, Mass Movement Processes and Landforms

Glacio-fluvial processes are created by glacial melt water either beneath or within or beyond the glacier margins. It can be documented in landscapes from past and present both. The glacio-fluvial system is mainly controlled by stability or fluctuations of a glacier regime- ice and ground temperatures, geothermal heating and function of air. Mass movements are also very common in the study area. Various type of mass movements are as follows:

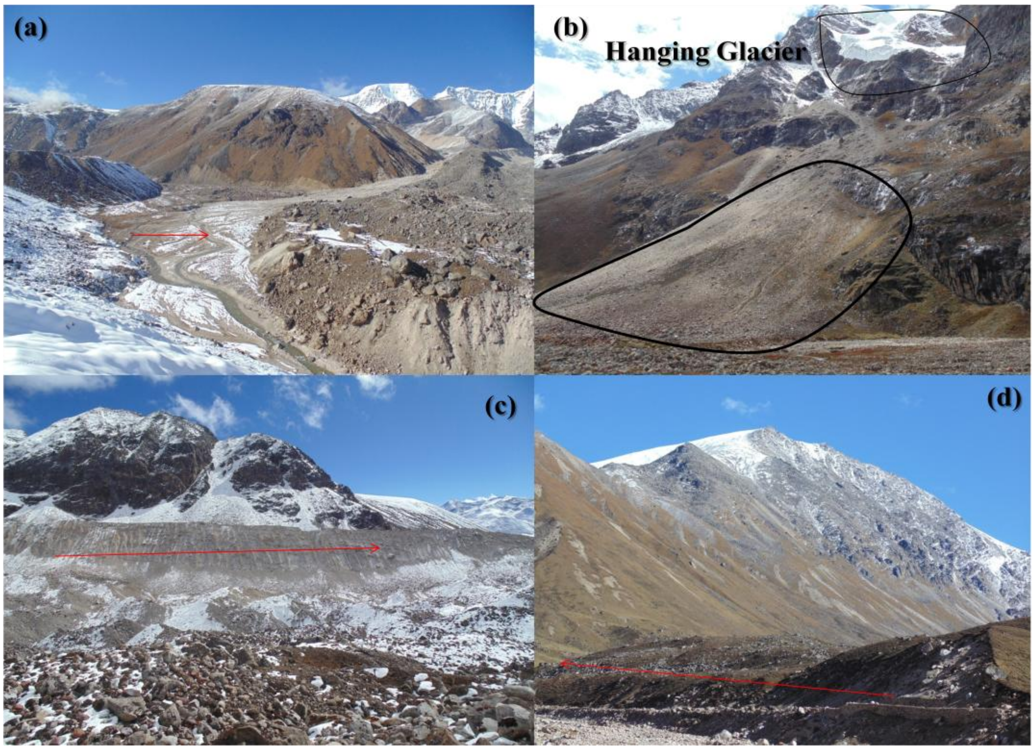
III.6.1 Glacio-fluvial Terraces: are predominantly located in glacier outwash area. These terraces are usually within 1 km of glacier snout and comprise poorly sorted sand, rounded and sub-rounded gravels. These terraces may indicate variable supply of melt-water or changes in snout position.

III.6.2 Snow Avalanche Cones:

Ice avalanche was observed on the right flank of the valley having steeper topography with angular rocky just formed by freeze and thaw action in a glacial area. Wherever there is snow lying on ground at sufficient angle, avalanche can take place and it plays an important role in debris transportation from higher elevations (Fig. III.15b).

Fig. III.13: Group of Earth Hummocks in red circle; flowing river has lots of deposition with debris fall in the area.

Fig. III.14: (a) Melt water streams in outwash plains and near the glacier area and active river channels **(b)** Hanging glacier and deposition of debris through avalanches or direct rock falls **(c)** closely spaced formation of gullies on lateral moraines of Changme Khangpu glacier **(d)** long stretch of moraine down the valley which are the evidences of last glaciations in Yumesamdong



III.6.3 Rockfalls, Rock and Debris Avalanches:

Rock-falls are broken rock down a vertical slope. Debris avalanches are common feature in the study area. Rock and debris avalanche often leads to formation of new landform or feature. The study area has witnessed formation of a new lake because of rock and debris avalanche back in the year 2011 (Fig. III.15a).

III.6.4 Scree, Debris Cones and Slope Failures:

Scree cover a slope of mountain in the form of small loose stones and broken rock fragments. It is usually accumulated due to periodic rock-falls from adjacent mountain cliffs and as a result landforms of talus deposit occurs. Debris cones are deposited in conical shape having surface slope greater than 10-15 degrees. In glacial valley's they are usually transported by snow avalanches as well as small streams. Similarly, slope failures are abrupt collapse of the weakened earth under the influence of rainfall or other triggering factors (Fig. III.16, III.17).

Fig. III.15: Field photograph showing **(a)** rock fall/rock avalanche, **(b)** series of snow avalanches, **(c)** formation of a new lake due to rock avalanche in Yumthang valley and **(d)** snow avalanche cones

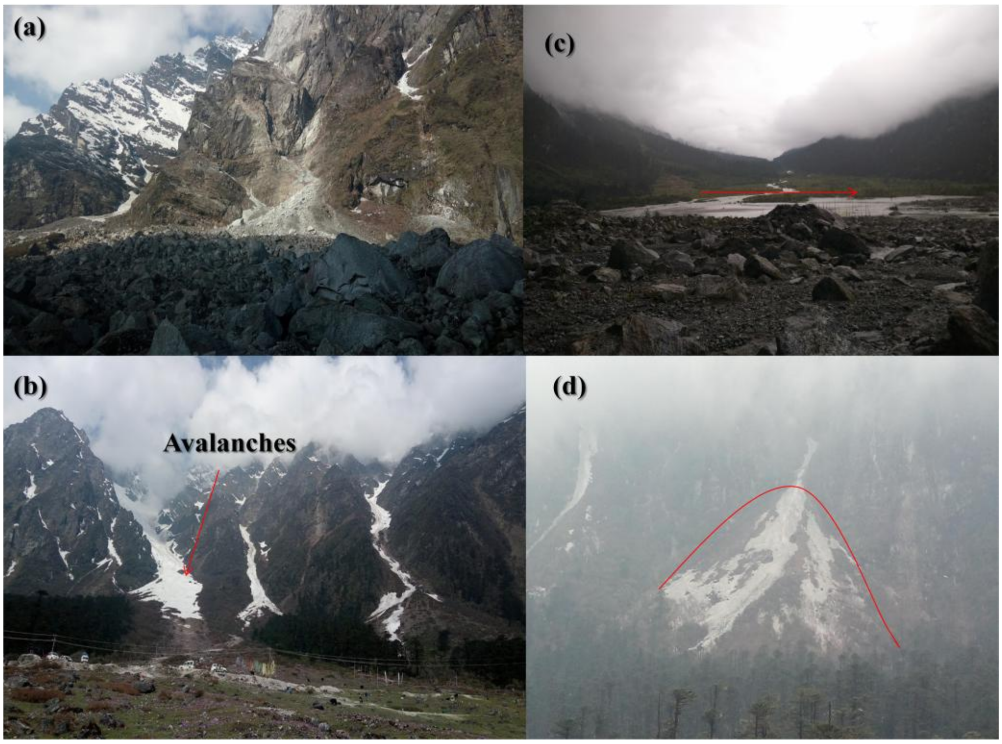
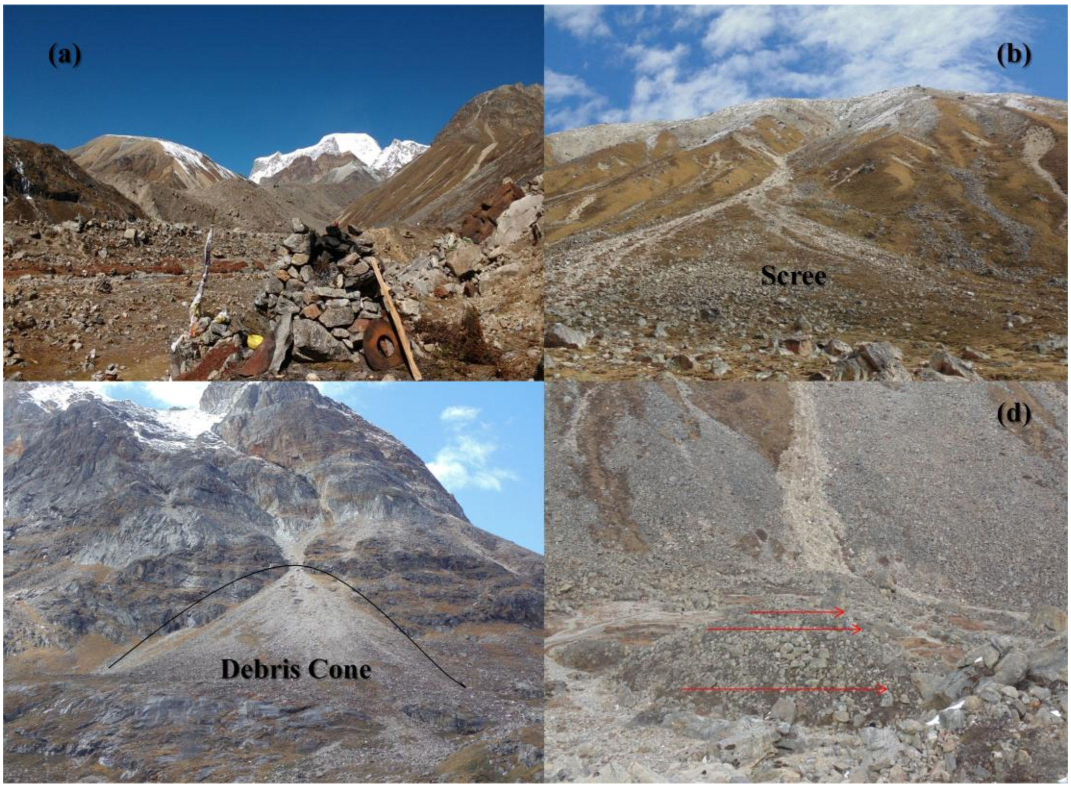


Fig. III.16: Field photograph showing rockfall along the slopes of the valleys near Yumesamdong

Fig. III.17: (a) Steep topography along with rock and debris fall, **(b)** scree deposit **(c)** debris cone and **(d)** stages of glacier in form of moraine deposition



Individually, each glacier behaves in a different manner corresponding to the factors such as morphology of valley, shape and size, aspect and slope, precipitation and temperature pattern etc. However, there is large number of glaciers which retreated fast, and some with reduction in retreat rate and are constant during the same period of observations.

In total, 58 glaciers were identified which varies between 0.28-22.54 km^2. The basin is characterized into five elevation zone with the main focus on glaciated area (i.e. Zone III 3500 m to Zone V5500 m and above). The basin has widespread highly debris-covered ablation zone which signify the area to be under higher melting condition. Total area under clean glacier is ~50.19 km^2 which is around 71 % of the total glacier area and higher than debris covered glacier which accounts for 28.99 %. Though the percentage of clean glaciers is higher in the basin as compared to the debris cover glaciers but the average size of debris covered glacier is much larger than the former. Retreat rate of debris covered glacier is faster than that of clean glaciers. In general, the glaciers in the Himalaya lies above 3500 m a.s.l and in the Sikkim Himalaya, Changme Khangpu basin, glaciers elevation ranges between 4000 to 7000 meters.

Geomorphic processes have carved out the landscape of the Changme basin. Concentrations of rockfalls are generally prevalent in the extreme north and south of the basin. Rockfalls in the north at an altitude of about 4000 meters or above may be caused by disintegration of rocks by solar insolation, freeze and thaw action, abrasion and plucking by glaciers releasing the sediments and debris with the melt water; while those in the southern part (1500–3000 m) are mainly attributed to higher rainfall and jointed rock structure. Moraines are found at an elevation of 3000 meters and above; these are usually large often running into kilometres. Glacial lakes are only encountered within the Frigid Zone. These are main source of fresh water for the downstream-valley population. Other features that could be observed are glacial till, valley terraces, cirques, etc. Development of numerous gullies by the glacial meltwater are also formed in the basin. This proves that Changme basin has dominant glacial processes active in the northern parts, while presence of braided channels, gullies, river terraces, bar deposits, etc. prove the fluvial processes are dominant in the other half of the basin.

Number of glacial lakes have increased over period of time indicating receding glaciers in the region. This increases potential of glacial lake outburst as the lakes are often formed along edges of moraines. An increase in length of lateral moraines has also been observed indicating the reduced glacierized area in the basin.

Chapter IV

<u>Glacio-fluvial Processes</u>

Glacier landforms shows the evidences of glacier behavior and health in any region, whether retreating or advancing. Similarly, glacial processes taking place in a glaciated valley presents sediments characteristics and mineral content, its physical and chemical weathering process. In addition, it also helps in understanding the provenance of these landforms and features and how it varies with its travelling distance in a river basin further downwards.

IV.1 Glacial Deposits from Changme Khangpu Glacier and their mineralogical characterization

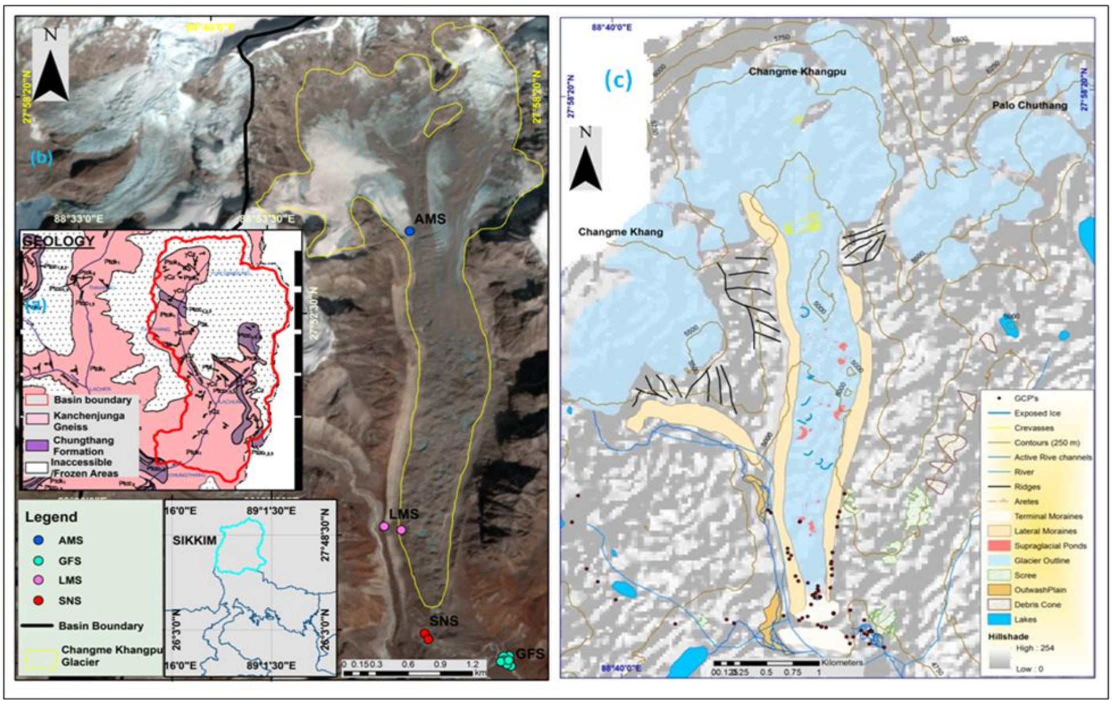
The Himalayan glaciers are the largest ice accumulations outside the polar regions and serve as an important glacial record (Bajracharya & Shrestha 2011; Bolch et al. 2012; Thompson et al. 2000; Owen & Benn, 2005; Seong et al. 2007; Owen 2009; Murari et al. 2014). In the present scenario, 70-80 % of the Himalayan glaciers are either thick debris-covered or with thin debris on the lower part and continuously pilling up since little ice age (Pratap et al. 2016; Sharma et al. 2016; Mal et al. 2019). Glacial sediments are transported from accumulation zone to the snout forming landforms like moraines, corrie or cirque (Hambrey & Glasser, 1978). The transport of sediments by glaciers is a very slow process, but it may be distributed over long distances.

The debris-covered Himalayan glaciers in north Sikkim, eastern Himalaya are flanked by large lateral and terminal moraines formed by reworking of supra-glacial debris by gravitational and glacio-fluvial processes (Benn & Owen 2002). The process of moraine formation at the glacier margin includes pushing the margin by glacio-fluvial deposits, dumping of supra-glacial debris and squeezing where fine-grained saturated sediments are present (Benn & Evans, 1996; Owen et al., 1996). The various glacial features e.g. lateral, medial and terminal moraines, pro-glacial lakes preserve the information about climate, erosion rate, deposition and tectonic evolution of the area (Smith 2000; Heimsath & MeGlynn 2008; Patel et al., 2016; Shukla et al., 2018). The glaciological studies are more focused on the western and central Himalaya, including remote sensing techniques, climate, geomorphology, sediment dating techniques, glacial hydrology and sediment transport dynamics (Taylor & Mitchell 2000; Bali et al., 2011; Shekhar et al., 2010; Juyal et al., 2010; Ray et al., 2011; Ray and Srivastava 2010; Ali et al., 2013; Sati et al., 2014; Sharma et al., 2016). However, in the Eastern Himalaya such detail studies are lacking to explain the geomorphic processes like evolution of glacial lakes, glacio-fluvial transportation and glacial sediment accumulation mechanism (Kulkarni et al., 2011; Basnett et al., 2013; Abrahami et al., 2018; Dubey et al., 2019; Garg et al., 2019; Shukla et al., 2018).

The sediments characteristic in the glacial environment is a function of lithology and geochemical properties of the sediment source, nature, distance of sediment transport, and the mode of sediment deposition (Owen et al., 2003; Dyurgerov & Meier 2005). Glacio-fluvial deposits, texture, and sorting can change radically over short distances if stream energy during deposition is variable in time and space. The texture of glacial till and related diamictites is controlled both by source and mode of deposition (Melvin et al., 1992; Bingham et al., 2010; Saha et al., 2016). Further, the grain-size analysis associated with sediment transport patterns can be used to describe the grain-size trends to characterize ancient and modern environments. Therefore, the textural and mineralogical assemblage are significant in glacial study. The present study mainly focuses on the textural and mineral composition of sediments, from the accumulation zone to outwash plain of Changme Khangpu Glacier revealing its physical and dynamic processes. Moreover, the local geomorphology, textural and mineralogical characteristics of glacial deposits are important and used for understanding of landform processes and depositional sedimentary environment.

The Changme Khangpu Glacier (27° 53’ 43’’ N, 88° 41’ 17’’ E) lies in the Changme Khangpu basin of eastern Himalayan region. The glacier is 5.65 km long and covers a glacier area of ~4.85 km^2. The elevation in the glacier valley ranges from 4850 to 5650 m a.s.l with a slope of <10°. The ablation area of the glacier is heavily debris-covered ~80-90% of the total area (Raina and Srivastava 2014; Pratap et al., 2016). The glacier has many seasonal supra-glacial lakes that change with time and space. The area in the vicinity of Changme Khangpu Glacier comprises of Central Crystalline Gneissic Complex (CCGC) and Kanchenjunga Group of rocks comprising gneisses (GSI 2012). These rocks are hard, compact and heavily jointed and at places intruded by tourmaline granites and pegmatites. The rock types are represented mainly by high grade metamorphic of the Central Crystalline Gneissic Complex (Ghosh et al., 2002; Anbalagan et al., 2014). The basin geology does not show much variation in the region as the whole basin covered with Kanchenjunga Gneiss and a small part of basin consist of Chungthang Granite Gneiss (Fig. IV.1a). Tundra like climate has been noticed in higher reaches of north Sikkim characterized by very low temperature and temperate climate in the lower reaches of the valley. The various geomorphic units found are- aretes, cirque, lateral moraines, supra glacial lakes, end moraines, outwash plains and snout of the glacier and out of which four accessible geomorphic units were selected for the present glacier sediment study namely-accumulation zone (AMS), lateral moraines (LMS), snout (SNS) and outwash plains (GFS) (Fig. IV.1b,c).

Fig. IV.1: (a) Geological map of the basin with the basin boundary **(b)** Location of sediments collected from Changme Khangpu glacier catchment in the Sikkim Himalaya, India. Symbols in different color is the site of sediment collection and yellow color shows the glacier boundary. **(c)** shows the detailed geomorphology of the glacier and nearby areas containing different features and landforms.



Source: **(a)** Geological map–by GSI, 2012 and **(b)** the background image is Sentinel-2A MSIL1C, 10th Oct. 2018, having 10 m spatial resolution downloaded from Copernicus Hub.

IV.1.1 Sampling Site

Fieldwork was carried out from the proglacial zone until the accumulation zone in the Changme Khangpu glacier catchment area to identify different types of geomorphic landforms and features. The geomorphic features observed includes U-shape valley, recessional moraine, melt-water streams, outwash plain, glacier snout, lateral moraines and accumulation zone. The geomorphic features identified in the field are GFS, SNS, LMS, and AMS, respectively, for sample collection (Fig. IV.2). Total thirteen sediment samples were collected from four different sites highlighting source areas of Changme Khangpu basin with co-ordinates of sample collection (Table IV.1).

The target sample size was mainly focusing on collection of sediments of finer size fractions less than granules. The outwash plain deposit is characterized by three small streams which are flowing in western, central and eastern part of deposit. Therefore, the samples are representative of western, central and eastern part of outwash plains from different sources. These glacio-fluvial sediments show a wide range of variation in the size distribution. GFS- 1, GFS- 5, and GFS- 7 were collected from the same stream, which is located in western part of this deposit. The GFS- 3, GFS- 6 and GFS-11 sediments were collected from stream two located in central part of these deposits. Another, sample GFS- 2 was collected from the stream which is located eastern part of this deposit. The samples collected are of finer type on an average than pebble size sediments.

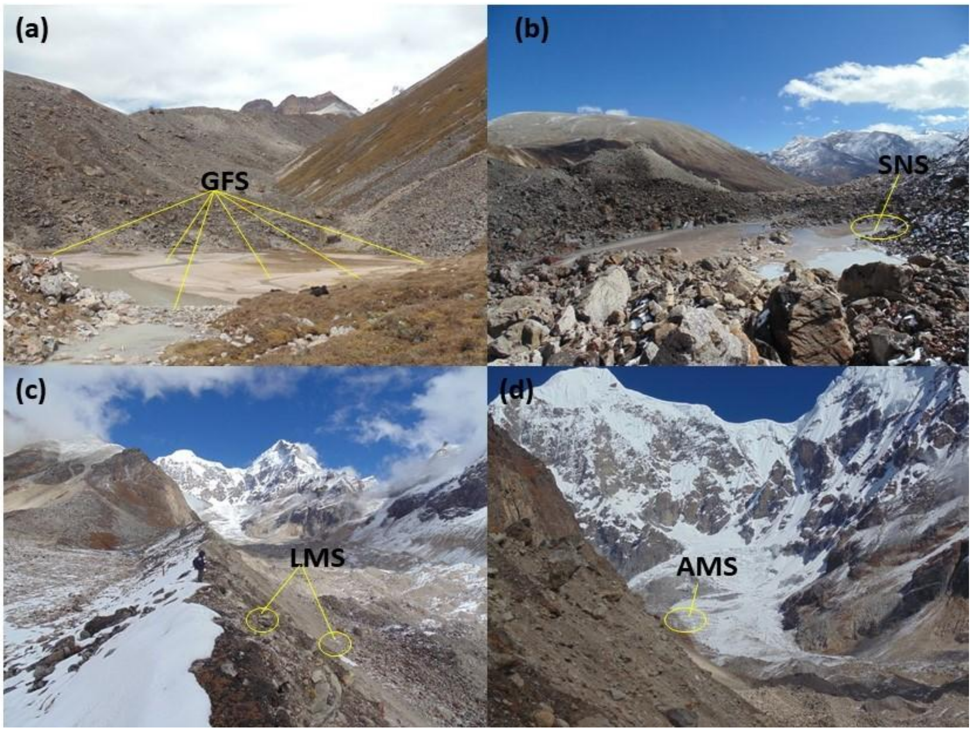
The methodology adopted here for textural study includes the samples dried at room temperature followed by coning and quartering to reduce the sample size without any systematic bias in representation of the size fraction using grain size analysis. The samples then were put through an automated Sieve Shaker for 30 minutes. After sieving, all the sieve size samples were collected separately and their masses have been recorded using Sartorius weighing balance (CPA26P), with 21g (d= 0.02 mg) resolution. Here, the statistical frequency parameters such as the graphic mean, inclusive of graphic standard deviation, graphic skewness, and graphic kurtosis was calculated using *Gradistat* (Blott & Pye, 2001). We have used the Folk & Ward (1957) method to determine these textural parameters interpreted by calculating the phi (φ) value which provides information about textural attributes of a particular environment.

The powder X-ray Diffraction (p-XRD) was performed after grain size analysis to identify the mineral assemblage of glacial sediments. After the sieve size samples were seperated in different size fragments, 30 gram of sample having the size fractions less than 53 microns was grinded using planetary ball mill grinding machine for the mineralogical analysis. The sediment grain size fraction of <53 micron comprises of clay and silt materials. The silt production in glacial processes is resultant product of glacial flour, while the formation of clay is process of chemical alteration. Therefore, physical weathering product as silt and chemical weathering as clay minerals need to target in the mineralogy to understand overall weathering processes operating in the region. The mineralogical analysis was performed using PAN-analytical X'Pert-Pro XRD (p-XRD). Each individual mineral was identified (XRD count analysis) by using X-pert High Score Plus Software and COD Database file for reference.

Table IV.1: The location point of sample collection and its geomorphic configuration.

Location	**Latitude**	**Longitude**	**Elevation from present river bed (in meter)**	**Distance from Snout (SNS-9) (in km)**	**Geomorphic Setup**
AMS- 12	27°57'37.081"N	88°41'0.229"E	558.10	3.98	Accumulation zone of glacier
LMS- 8	27°56'03.86"N	88°40'52.38"E	259.08	1.15	Lateral moraine
LMS- 10	27°56'02.44"N	88°40'57.31"E	235.61	1.10	Lateral moraine
SNS- 4	27°55'29.95"N	88°41'04.70"E	127.10	0.07	Snout of glacier
SNS- 9	27°55'30.28"N	88°41'04.82"E	121.62	-	Snout of glacier
SNS- 13	27°55'27.92"N	88°41'07.20"E	122.84	0.04	Snout of glacier
GFS- 1	27°55'19.49"N	88°41'30.788"E	39.32	0.75	Outwash plain
GFS- 2	27°55'20.04"N	88°41'29.607"E	36.58	0.70	Outwash plain
GFS- 3	27°55'21.37"N	88°41'30.118"E	42.06	0.69	Outwash plain
GFS- -5	27°55'22.73"N	88°41'30.209"E	42.06	0.69	Outwash plain
GFS- 6	27°55'20.93"N	88°41'27.768"E	42.06	0.64	Outwash plain
GFS- 7	27°55'21.32"N	88°41'28.788"E	42.06	0.66	Outwash plain
GFS- 11	27°55'22.63"N	88°41'28.598"E	42.06	0.65	Outwash plain

Fig. IV.2: Overview of the study area and sample location sites in the Changme Khangpu glacier (a) outwash plain (b) snout (c) lateral moraines and (d) glacier accumulation zone.



The grain size distribution affect largely mineralogical composition of sediments where each type of mineral contributes to specific size range of sediments. Therefore, each grain size fraction provides valuable results for understanding the process of formation as physical or chemical weathering, than use of bulk sediment samples (Zhou et al. 2014; He et al. 2015).

The present work is first attempt for the study of linkage between grain size composition and mineral characterization including the glacierized basin part of eastern Himalaya. We used grain size as a most effective tool for the study of sediment environment and landform association. In glacial environmental processes the differential grain size fractions of sediments are produced as result of glacial weathering and erosion, which are transported by glacial ice and water then accumulated in the form of different landforms. In this environment the moraines are characterized by differential size fractions than fluvial outwash plains.

The method opted for the study can be supported by Blott & Pye (2001) who have mentioned that Folk & Ward (1957) methods is the most robust method for comparison of compositionally variable sediments. Similar kind of study in other parts of Himalaya has been done (Ray et al., 2011; Sati et al., 2014). But these studies are mostly focused on tectonic sediments, river sediments and their grain size analysis (Duller et al., 2010; Mishra & Chakrapani 2014; Guerit et al., 2018). Glacial sediment study is difficult to find as most of the studies focuses on chemical characterization of the sediment fluxes rather than study of grain size analysis and mineral assemblage, however few studies in western Himalaya and in other parts shows the relationship between sediment flux and gravel size composition (Khatawa et al. 1999; Smith 2000; Surian 2001; Hart & Rose 2001; Shrivastava et al. 2014; Attal et al. 2015; Haldorsen 2015; Panwar et al. 2016; Kumar et al. 2018; Parida et al. 2019, Shukla et al. 2020).

IV.1.2.1 Textural Characteristics of the Sediments

The texture and size fraction of sediments helps to understand the transporting agent and energy condition. The grain size analysis provides the distribution of different size fraction in sediments. The different statistical parameters as mean, sorting, skewness and kurtosis also suggests about relative contributions of different size fractions. Table IV.2 shows the statistical range of textural analysis from each sampling site.

(a) Glacio-fluvial Sediments (GFS) The sediments were mostly fine size as textural group indicates it as muddy-sand dominance. This is also supported by skewness as indicating coarsely skewed. The sediments are mostly dominated by fine fraction but some also show mixed size fraction. The sorting also shows these samples are of moderately to poorly sorted nature. The kurtosis indicates a variation from platykurtic to leptokurtic nature (Fig. IV.4, Table IV.2).

The sizes mostly were of mixed nature, both coarse as well as fine sediments in samples of GFS- 3, GFS- 6 and GFS- 11. The size fractions are comparatively coarser than that of sediments collected from stream one as inferred by mean inferring medium to fine sand. The skewness shows symmetrical to fine skewed indicating coarser size fraction dominance. The sorting also suggests moderately to poorly sorted nature, reflecting contribution of mixed size fraction. It is also indicated by kurtosis which is platykurtic to leptokurtic in nature. Therefore, these samples indicate considerably fluctuating and high energy condition of transportation agent. The sample GFS- 2 shows coarse sediments are dominant over finer size fractions. This sample is poorly sorted in nature supplemented by the bimodal nature. The skewness is symmetrical and the kurtosis is platykurtic nature which indicates more than one size domain is contributing to a higher amount (Table IV.2, Fig. IV.4).

Overall, the textural analysis of samples collected from glacio-fluvial areas show mean variation from medium sand to very fine sand. The sorting is dominated by poorly sorted nature of mix grain size fraction contribution indicative of glacial clasts. Therefore, the energy condition of the transporting agent reveals changing from high to low.

(b) Lateral Moraines (LMS) The results of LMS- 8 and LMS-10 show sand as main textural group and medium sand is the dominant fraction as indicated by the mean value. The skewness value infers symmetrical nature which indicates that coarse as well as fine sediments are present. This also supports sorting of sediments as poorly sorted nature because of the presence of mix size fractions. The kurtosis shows the platykurtic nature which infers presence of coarser to finer size fractions. The finer size sediments are more abundant in lateral moraines. Therefore, the energy condition during deposition of sediment is inferred as fluctuating.

Table IV.2: Grain size of different geomorphic features in the Changme Khangpu Glacier catchment

Sample	Mean in (phi)	Grade	Class	Sample Type	Textural Group	Sorting	Skewness	Kurtosis
Glacio-fluvial (GFS)								
1	1.913	Medium sand	Sand	Unimodal, Poorly sorted	Muddy sand	Poorly sorted	Coarse skewed	Platykurtic
2	1.324	Medium sand	Sand	Bimodal, Poorly sorted	Sand	Poorly sorted	Symmetrical	Very Platykurtic
3	1.920	Medium Sand	Sand	Bimodal, Poorly sorted	Sand	Poorly sorted	Fine skewed	Leptokurtic
5	2.234	Fine Sand	Sand	Trimodal, Poorly sorted	Sand	Poorly sorted	Coarse skewed	Leptokurtic
6	1.253	Medium sand	Sand	Bimodal, Poorly sorted	Sand	Poorly sorted	Fine skewed	Very platykurtic
7	3.039	Very fine sand	Sand	Bimodal, moderately sorted	Muddy Sand	Moderately sorted	Coarse skewed	Mesokurtic
11	3.391	Very fine sand	Sand	Unimodal, moderately sorted	Muddy sand	Moderately sorted	Symmetrical	Platykurtic
Snout (SNS)								
4	3.445	Very fine sand	Sand	Unimodal, moderately sorted	Muddy sand	Moderately sorted	Symmetrical	Platykurtic
9	3.367	Very fine sand	Sand	Unimodal, moderately sorted	Muddy sand	Moderately sorted	Symmetrical	Platykurtic
13	2.812	Fine sand	Sand	Unimodal, moderately sorted	sand	Moderately sorted	Coarse skewed	Platykurtic
Lateral Moraines (LMS)								
8	**1.427**	Medium sand	Sand	Trimodal, Poorly sorted	Sand	Poorly sorted	Symmetrical	Very platykurtic
10	1.585	Medium sand	Sand	Trimodal, Poorly sorted	Sand	Poorly sorted	Symmetrical	Very platykurtic
Accumulation Zone (AMS)								
12	1.346	Medium sand	Sand	Bimodal, Poorly sorted	Sand	Poorly sorted	Coarse skewed	Very platykurtic

(c) Snout Sediments (SNS)

Samples SNS- 4, SNS- 9, and SNS- 13 from the snout of the Changme Khangpu Glacier shows the dominance of fine size fraction. The mean value infers fine to very fine sand while the skewness ranging from symmetrical to coarsely skewed which shows contribution from mix to fine size fractions of sediments (Table IV.2). These samples show platykurtic nature which indicates more than single size domain contributes to the samples in a higher amount (Fig. IV.4). The sediments are dominated by silty sand texture. The samples are of unimodal nature which infers the constant energy condition of transportation agent.

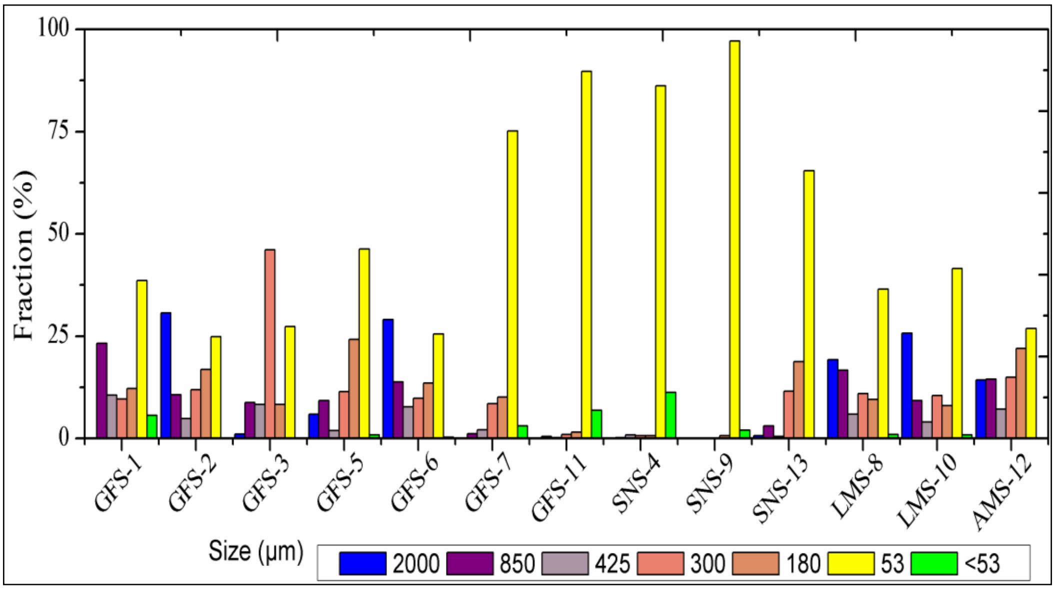
(d) Accumulation Zone (AMS)

It is apparent that the mass distribution of the different size of sediments from the accumulation zone is relatively variable. However, fine sediments are relatively dominant (Fig. IV.3). The textural group of the sediment type is sand and medium sand is dominant as indicated by the mean. The sorting of the sediment is poorly sorted and is supported by the bimodal nature of the sediments (Table IV.2). It is inferred from skewness that the sediment particles are of coarse skewed nature (i.e. an increase in fine-grained sediments than coarse size). Kurtosis of the sample shows the platykurtic nature that indicates a contribution from all size fractions and this means variable energy condition of the sediments during deposition.

IV.1.2.2 Comparative Distribution of Statistical Parameters

The textural parameters as contribution of sand, silt and clay in sediments shows GFS and SNS sediments are dominated by finer fractions like silty sand while AMS and LMS sediments are comparatively of coarser fractions as sand is dominant (Fig. IV.3). This indicates the GFS and SNS areas are influenced by comparatively high energy conditions of transporting agent than AMS and LMS.

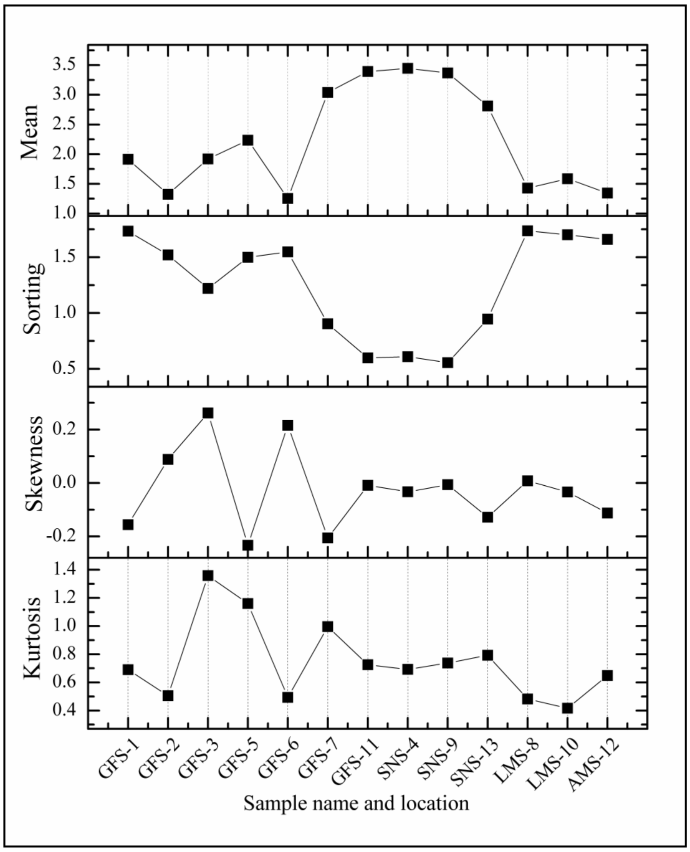
Fig. IV.3: Mass distribution of grain size sediments, Changme Khangpu Glacier catchment.



The distribution of the mean shows clustering in the range of 1 to 4 phi units which falls into the category of medium to very fine sand. The sediments of accumulation zone, lateral moraine show coarser fraction contribution than snout sediments while glacio-fluvial sediments show variable size fraction from fine to medium (Fig. IV.3). The sorting is clustering in the range between 0.50 and 2.0 which falls into the category of moderately sorted to poorly sorted. The poor sorting means that there is a wide range of mixed size fractions and the samples from the accumulation zone and lateral moraine show poorly sorted in nature than that of sediments from snouts. Whereas, glacio-fluvial sediments show a mixed nature as represented by poor to well sorting (Fig. IV.4). The skewness falls into the category of fine to coarse skewed (-0.30 to 0.30) which infers the contribution of both fine-grained as well as coarse-grained sediments. Therefore, nearly symmetrical distribution is dominant in sediments of accumulation zone and lateral moraine. The snout sediments infer contribution of the coarse as well as finer fractions while that of glacio-fluvial sediments shows wider variation from fine to coarsely skewed.

The kurtosis distribution shows clustering in between 0 and 1.50 (Fig. IV.4), which falls into the category of platykurtic to leptokurtic and also infers all size sediment fractions contributing in higher amount referring to fluctuation in energy condition during deposition. The platykurtic dominance is found in sediments collected from accumulation zone, lateral moraine and snout which indicate finer as well as coarse size dominance, while in that of glacio-fluvial sediments few samples are inclined towards leptokurtic nature as a part of the fluvial system.

Fig. IV.4: Statistical spatial distribution of the samples from various locations



Sediments from accumulation and lateral moraine are poorly sorted in nature but the former is dominated by fine sediments and the later is coarse-grained. The sediments from snout are moderately sorted with mixed size fraction but single size is dominating while that of glacio-fluvial sediments are moderate to poorly sorted and fine dominance more than one size fraction. Therefore, the textural analysis infers that the sediments from accumulation zone and lateral moraine are the product of dynamic processes of transporting agent as high energy fluvial condition contributes to the formation of these sediments. While the sediments from the snout area reflect comparatively high-water supply tend to moderately well-sorted sediments. The sediments collected from glacio-fluvial area infer that they are deposited in fluctuating energy condition of transporting agent. The snout and glacio-fluvial sediments also suggests influence of fluvial derived landform processes like, outwash plains, river terraces.

IV.1.2.3 Mineralogical composition

The results of p-XRD analysis of these glacial sediments from accumulation zone, lateral moraine, snout and outwash plain collected from Changme Glacier have been presented in (Table IV.3). The different mineral assemblage gives knowledge about the source and type of weathering conditions occurring at such high-altitudes. The mineralogical assemblages from sediments of glacial catchment are identified as- a) garnet, goethite, microcline, orthoclase, quartz in accumulation zone of the glacier catchment, b) anorthite, garnet, goethite, magnetite, microcline, orthoclase, and quartz from lateral moraines, c) anorthite, garnet, goethite, magnetite, microcline, quartz from snout and indicates a medium to high-grade metamorphic source for the sediments deposited at the snout, d) albite, anorthite, garnet, goethite, mica, microcline, phlogopite, and quartz found in the sediments of outwash plains of the catchment area.

The mineral assemblages in sediments are dominated by felsic minerals like quartz, albite, anorthite, orthoclase, and microcline. Mica minerals like biotite, muscovite, and phlogopite along with metamorphic alumino-silicates minerals like garnet are also identified. Several samples show presence of alteration mineral like goethite. The presence of quartzo-feldspathic, mica and alumino-silicate minerals like garnet in the sediments indicate that they were derived from medium to high grade metamorphosed felsic terrain, whereas goethite indicates chemical alteration of the minerals like mica. Therefore, the mineralogical assemblage of these glacial sediments indicates that physical weathering processes, are dominating in the upper part of the basin than chemical weathering. The provenance of these minerals is from the gneissic rocks of Greater Himalayan sequence.

Table IV.3: p-XRD specifications of all the samples of study area and mineral assemblage in the sediments

Sample	**Mineral**	**Pos. [°2Th.]**	**Height [cts]**	**FWHM Left [°2Th.]**	**d-spacing [Å]**
GFS-1	Quartz	26.6305	12130.08	0.0816	3.34463
	Anorthite	27.8985	1125.74	0.2448	3.19543
	Microcline	50.1296	1462.46	0.1224	1.81828
	Garnet	67.7413	765.5	0.1224	1.38215
GFS-2	Goethite	21.1230 (9)	1854 (39)	0.104 (3)	4.2026
	Quartz	26.9017 (4)	8915 (77)	0.110 (2)	3.31153
	Albite	27.924 (4)	731 (11)	0.69 (1)	3.19257
	Microcline	50.4034 (6)	2097 (42)	0.076 (2)	1.80904
	Garnet	60.188 (1)	875 (18)	0.134 (3)	1.53624
GFS-3	Goethite	21.158 (1)	1492 (22)	0.212 (3)	4.1957
	Quartz	26.9326 (5)	8754 (61)	0.167 (2)	3.3078
	Phlogopite	36.863(1)	1083(24)	0.132(4)	2.43634
	Microcline	50.4240 (9)	1520 (29)	0.118 (3)	1.80834
	Garnet	60.221 (1)	1009 (17)	0.161 (3)	1.53547
GFS-5	Goethite	21.401 (1)	1074 (20)	0.176 (3)	4.14864
	Quartz	27.1660 (4)	8348 (66)	0.128 (1)	3.27991
	Albite	28.423 (2)	1340 (18)	0.360 (7)	3.13766
	Mica	37.068 (2)	662 (18)	0.146 (5)	2.42336
	Microcline	50.618 (1)	998 (20)	0.147(4)	1.80185
	Garnet	60.437 (1)	880 (17)	0.149 (3)	1.53049
GFS-6	Goethite	21.0130 (5)	3217 (62)	0.065 (2)	4.22436
	Quartz	26.7828 (6)	6312 (52)	0.175 (2)	3.32596

	Anorthite	28.009 (2)	1195 (24)	0.243 (8)	3.18313
	Microcline	50.2705 (6)	1831 (31)	0.091 (2)	1.81351
	Garnet	60.1172 (7)	1633 (34)	0.083 (2)	1.53788
GFS-7	Goethite	21.234 (2)	722 (16)	0.228 (5)	4.18094
	Quartz	27.0187 (7)	4720 (42)	0.190 (2)	3.29746
	Quartz	28.2042 (9)	2154 (38)	0.130 (4)	3.16149
	Microcline	50.4685 (5)	2515 (46)	0.074 (2)	1.80686
	Garnet	60.291 (2)	691 (14)	0.229 (6)	1.53387
GFS-11	Goethite	21.097 (1)	1634 (24)	0.196 (3)	4.20778
	Quartz	26.8744 (5)	8067 (60)	0.185 (2)	3.31484
	Microcline	50.3949 (9)	1288 (24)	0.111 (3)	1.80932
	Garnet	60.2157 (9)	1448 (30)	0.105 (3)	1.53559
AMS-12	Goethite	21.217 (1)	1846 (28)	0.161 (3)	4.18428
	Orthoclase	26.9933 (3)	11640 (81)	0.121 (1)	3.3005
	Quartz	28.171 (3)	1075 (12)	0.585 (7)	3.16517
	Microcline	50.4753 (8)	1732 (30)	0.109 (3)	1.80663
	Garnet	60.2853 (9)	1368 (24)	0.121 (3)	1.53399
LMS-8	Goethite	21.1426	2608.44	0.1506	4.20224
	Orthoclase	26.876	15834.44	0.1506	3.31738
	Anorthite	27.8862	3339.14	0.1338	3.19946
	Quartz	28.2103	8974.89	0.0669	3.16344
	Microcline	50.3834	1739.93	0.2676	1.81121
	Garnet	60.2276	960.49	0.2676	1.53659
LMS-10	Goethite	21.0903 (7)	3006 (41)	0.126 (2)	4.20906
	Orthoclase	26.8493 (3)	16009 (92)	0.120 (1)	3.31788
	Quartz	28.039 (2)	1687 (15)	0.542 (4)	3.17979
	Magnetite	36.7582 (7)	1590 (34)	0.083 (2)	2.44304
	Microcline	50.3416 (6)	2301 (40)	0.093 (3)	1.81111
	Garnet	60.1490 (7)	1955 (30)	0.109 (2)	1.53714
SNS-4	Goethite	21.2852	1261.97	0.1632	4.17095
	Quartz	27.0639	11109.83	0.0816	3.29205
	Anorthite	27.9049	3958.04	0.2448	3.19471
	Microcline	50.5275	2053.35	0.102	1.80488
	Garnet	60.306	888.62	0.4896	1.53351
SNS-9	Goethite	21.216(1)	1170(19)	0.228(3)	4.18444

	Quartz	26.9680(2)	16492(89)	0.1022(7)	3.30354
	Magnetite	35.7791(4)	2649(46)	0.051(1)	2.50763
	Garnet	60.3094(4)	3123(45)	0.070(1)	1.53343
SNS-13	Goethite	21.0053(7)	2497(36)	0.120(2)	4.22588
	Quartz	26.7827(3)	13109(87)	0.127(1)	3.32597
	Anorthite	28.000(2)	1657(14)	0.573(5)	3.1841
	Microcline	50.2927(7)	1961(35)	0.094(2)	1.81276
	Garnet	60.1026(8)	1475(26)	0.110(2)	1.53821

The linkage between grain size composition, textural and mineralogical characteristics of the Changme Khangpu Glacier, North Sikkim, were studied and evaluated for the relationship between different landform and geomorphic features of the glacier and depositional environment. The textural studies based on grain size analysis shows coarser as well as fine size fractions in variable proportion. The sorting of the sediments varies widely between poorly sorted to moderately sorted indicating glacial and glacio-fluvial processes were operational over the area. The skewness differs from symmetrical, coarse skewed and fine skewed infers mixed size fractions of sediments. In the upstream (AMS-12), the sediments are fine skewed and in the downstream sediments are coarse skewed which supports that the sediments are coarser upstream and get finer after long distance travel. This is also supported by kurtosis of sediments indicating differential transportation and depositional processes operating at different parts of glacier. The change in modality of samples from unimodal, bimodal and trimodal confirms fluctuation in energy conditions of transporting agent. Grain size decreases with the stream distance and coarse sediments away from the source site indicates that the velocity of the stream was very fast. The present study concludes that depositional landforms of accumulation zone and lateral moraines are developed through comparatively more dynamic glacial processes while snouts and glacio-fluvial regions are developed in response to fluvial processes. The grain size and mineralogical study shows that the sediments are almost similar in their compositon in all the sites. The mineralogical studies of finer fractions of sediments by p-XRD method indicate identical mineral assemblage of source rock as presence of quartzo-feldspathic, mica and alumino-silicate minerals in the sediments indicate that they were derived from medium to high grade metamorphosed terrain of Central Crystalline Gneissic Complex (CCGC) of the northern Sikkim, whereas goethite indicates chemical alteration. The mineral assemblage recorded in the finer size fractions of glacial sediments also indicate contribution is mainly from physical weathering process compared to chemical weathering.

IV.2. Mineralogical variation of channel sediments deposited through glacio-fluvial activities along Teesta river

Sediment plays a vital role in understanding the transportation and the depositional environments of any area. The nature of sediment provides the basis for understanding the climate and environmental conditions under which the sediments were transported and deposited in geological past (Garzanti et.al., 2004; Alharbi et. al., 2016). The complex processes that operated in the past also operating today and have left some imprints in the present sediments (Lukramet et al., 2007; Singh, 2010). The transportation of sediments is not constant, and sediments can be altered during transportation. The alteration of sediments occurrs due to changes in river water flow, level of water, weathering and erosional events (Issaka and Ashraf, 2017). The sediment deposited at the bank of river also varies in physical and chemical properties throughout the area (Sundarjan et al., 2009), as the deposition of these sediments starting from the source area of the basin are due to glacio-fluvial activities taking place in the basin. The deposition is associated with low energy environments the fine-grained material accumulates; whereas, if erosion dominates, sediment is over consolidated. The variation in grain size from source area reflects the nature of sediments, estimated the distance of transportation, mineralogical characteristics reflects the environmental changes and the influences of human interference (Rashedi and Siad, 2016; Maity and Maiti, 2016; Kanhaiya et al., 2017).

Assemblage of parent rocks may be studied by petrographic analysis of the sediments which helps to understand the mineralogical constituents, tectonic setting and paleoclimate reconstruction (Storlazzi and Field, 2000; Quasimet al., 2017). The provenance studies deduce the characteristics of source areas from measurements of compositional and textural properties of sediments (Haughton et al., 199; Critelli et al., 2003; Weltje and Eynatten, 2004). Compositional and textural characteristics of the initial detritus are modified by abrasion and sorting during transport, when sediments are carried away from their source area (Nesbitt and Young, 2008; Garzanti et al., 2017).The characteristic of particle size of the sediment is of great importance as many of the substances are bound to clay particles (Thomas and Meybeck, 1992; Udelhoven and Symader, 1995).

The sediments characteristic in the glacial environment is a function of lithology and geochemical properties of the sediment source, nature, distance of sediment transport, and the mode of sediment deposition (Dyurgerov & Meier 2005; Owen et al. 2003). Glacio-fluvial deposits, texture, and sorting can change radically over short distances if stream energy during deposition is variable in time and space. Whereas over long distances of travel through the river channels the grain size and mineral variation will be more. The present study is an attempt to understand how the sediment from higher altitude to lower altitude and deposition condition changes. To support the result of XRD for mineral presence and its texture, petrographic study has also been done. The recent work has more focused on the properties of the eroded material and their relationship to those of the source material which signifies the past depositional environments. Study of the depositional environment and tectonic setting is also very limited in eastern Himalyan region. The spatial variation on textural, mineralogical and petrographic characteristics of alluvial sediments are studied in specific area (Sensarma et al., 2008; Ghazi et al., 2019) but does not cover the entire strech in Sikkim Darjeeling Himalyan region.

IV.2.1 Sampling Site

Teesta River originates from different glaciers in northern part of Sikkim and the state lies in the upper basin of Teesta river. A small portion of the study area falls in the Darjeeling Himalaya as well. Two important tributaries of the river Teesta are Lachen *Chhu* and Lachung *Chhu*. The river originates from the glacier around Gurudongmar in North district of Sikkim as Lachen *Chhu* flows toward south where it joins Zemu *Chhu*, which originates from Zemu glacier in west Sikkim, at the upstream of Lachen Village. Lachung *Chhu* originates from glaciers around Yumesamdong in north Sikkim. Lachen *Chhu* and Lachung *Chhu* join at Chungthang in north Sikkim and afterwards it is known as river Teesta. On the basis of geological formation of Himalaya, the study has been divided into three stretches viz. upper stretch, middle stretch and lower stretch-(a) Upper stretch of river Teesta, in north district of Sikkim, comes under Higher Himalayan Sequences. Higher Himalaya/ Central Crystalline consist of medium to high grade rock dominantly of pelitic schist with inter-banded quartzite, calc-silicate and metabasites of Chungthang Formation overlain by Darjeeling Gneiss/Kanchenjunga Gneiss (GSI, 2012; Anbalagan et al. 2014). The elevation of this stretch ranging from 650 m to 4700 m. The average annual temperature is 0.1ºC and average rainfall ranging from 247 mm to 2650 mm. In this stretch, the vegetation cover is temperate, sub- alpine and mixed evergreen forest. (b) Middle stretch of Teesta river, from Singhik to Teesta Bazar comes under the Lesser Himalayan Sequence. The elevation ranges from 300 m to 650 m. The temperature varies in Lesser Himalayan part is between 4 ºC to 25 ºC and the average rainfall is around 3000 mm. The vegetation cover is tropical moist deciduous forest. (c) Lower stretch is, from Teesta Bazar to Sevoke southwest Darjeeling District of West Bengal, falls under Siwaliks which consist sandstones, shales, pebble beds, conglomerates etc

(Chakraborty et al., 2016). This region consists of huge sedimentary succession with low grade metamorphic rocks. The elevation of this stretch is below 300 m. The average temperature is around 35ºC and rainfall is more than 3000 mm. The vegetation cover is tropical.

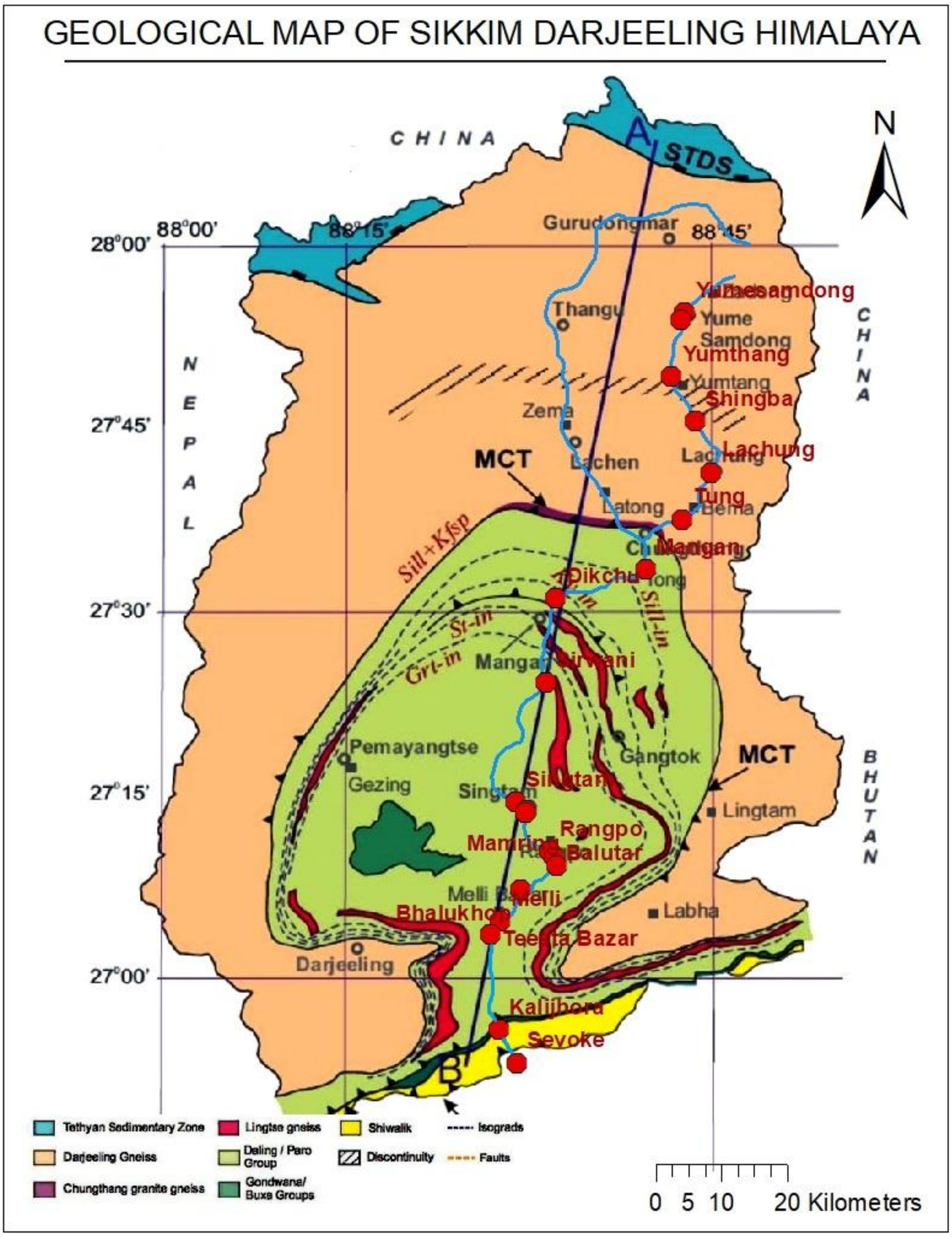
Total twenty samples of channel sediments were collected from Teesta river in Sikkim- Darjeeling Himalaya, as per EPA/CE-81-1 protocol (Plumb, 1981) (Table IV.4). Around 300 g of samples were collected at each site along the stretch of the river from Yumesamdong (4700 m a.s.l) in north district of Sikkim to Sevoke (126 m a.s.l) in Darjeeling district of West Bengal. Six samples are been taken from upper stretch, eleven from middle stretch and three samples were collected from lower stretch. These collected samples were kept air tight and at room temperature after taken to the lab.

The sample collection for this study stretched up to the whole Teesta River till Sevoke and the XRD, mineralogical and petrographic studies have been done to understand the nature of sediment along the stretch of river and also supporting the above study based on a single glacier.

(a) Textural Identification

The samples are dried carefully at room temperature on white sheet to avoid contamination. The bulk sample was reduced by coning and quartering methods. The sample was equally divided into four parts. Out of four parts, opposite two sides were taken for homogenization of sample. This process was repeated two or three times reducing the sample to 100g and then, 100g of weighted samples were poured into the sieve. The sample is processed at an interval of 15-20 minutes and after which all the sample from sieve were collected separately. The graphic mean, inclusive graphic standard deviation, skewness and kurtosis are calculated by using Gradistat software by plotting all the weighted individual sieve value of each sample. Folk and Ward method were used to determine these parameters interpreted by calculating the value of phi (φ).

Fig. IV.5: Study sites from Yumesamdong to Sevoke along the Teesta river. The red dots in the maps shows the sample site along the river stretch.



Source: Modified after Chakraborty et al., 2016

Table IV.4: Sample identity and brief description of sample site.

Sl. No.	Sample Identity	Name of Place	Latitude (N)	Longitude (E)	Elevation (m)
1	L1	Yumesamdong (1)	88°41´16.8´´	27°54´21.6´´	4700
2	L2	Yumesamdong (2)	88°42´39.6´´	27°54´07.2´´	4627
3	L3	Yumthang Valley	88°41´49.2´´	27°49´22.8´´	3659
4	L4	Shingba	88°43´58.8´´	27°45´46.8´´	3379
5	L5	Lachung	88°44´56.4´´	27°41´31.2´´	2597
6	L7	Tung	88°39´32.4´´	27°33´32.4´´	1308
7	L8	Mangan	88°32´13.2´´	27°31´12.0´´	746
8	L9	Dikchu	88°31´22.8´´	27°24´18.0´´	509
9	L10	Sirwani	88°28´58.8´´	27°14´56.4´´	258
10	L11	Singtam(1)	88°29´52.8´´	27°14´09.6´´	333
11	L12(1)	Singtam (2)	88°29´45.6´´	27°13´40.8´´	332
12	L12(2)	Singtam(3)	88°29´45.6´´	27°13´40.8´´	332
13	L13	Rangpo	88°31´58.8´´	27°10´48.0´´	286
14	L14	Balutar	88°32´27.6´´	27°10´33.6´´	258
15	L15	Mamring Forest	88°31´26.4´´	27°09´25.2´´	248
16	L16	Bhalukhop Forest	88°28´51.6´´	27°07´19.2´´	247
17	L17	Melli	88°27´18.0´´	27°05´16.8´´	200
18	L18	Teesta Bazar	88°25´58.8´´	27°03´28.8´´	196
19	L19	Kalijhora	88°27´32.4´´	26°55´51.6´´	136
20	L20	Sevoke	88°29´02.4´´	26°53´09.6´´	126

Table IV.5: Sorting, Skewness and Kurtosis of the sediments collected for grain size analysis

Sorting	Phi (φ)	Skewness	Phi (φ)	Kurtosis	Phi (φ)
very well sorted	<0.35	Strongly fine skewed	>+0.30	Very platykurtic	<0.67
well sorted	0.35 -0.50	Fine skewed	+0.30 to +0.10	Platykurtic	0.67 - 0.90
moderately well sorted	0.50 - 0.71	Near symmetrical	+0.10 to --0.10	Mesokurtic	0.90 - 1.11

moderately sorted	0.71 - 1.00	Coarse skewed	-0.10 to --0.30	Leptokurtic	1.11 - 1.50
poorly sorted	1.00 - 2.00	Strongly coarse skewed	<-0.30	Very leptokurtic	1.50 - 3.00
very poorly sorted	2.00 - 4.00			Extremely leptokurtic	>3.00
extremely poorly sorted	>4.00				

(b) Mineralogical Identification Using X-Ray Diffraction

Samples were dried at room temperature and around 30g of sample of mesh size above 50 ASTM has been taken for grinding into Planetary Ball Mill Grinding Machine. The mineralogical analysis was performed using PAN-analytical X'Pert-Pro XRD (p-XRD). Each individual mineral is identified (XRD count analysis) using X-pert High Score Plus Software and COD Database file for reference.

(c) Petrographical Study

Petrographic study has been made by using thin sections prepared from sediments collected from the field. Sediments of 80 mesh size separated for preparing the slide. The sediments are pasted on slide using the araldite and left for 1-2 days. After drying, for making thin film of sediments the slides thinning are done by using corundum powder of different sizes. Further, the mineralogical study of slides is studied under the microscope magnification 4X and model analysis plotted by using point counting methods manually. The works is carried out by identification of mineral constituents present in sediments and are calculated by normalizing the counts value of quartz, feldspar and lithic /rock fragments. Further study of this QFL plot is used in understanding the mineral assemblage and tectonic setting of the study area.

IV.2.2 Transportation Process and Mineral Variation

The grain size analysis is carried out to know the percentage of different grain sizes contained within sediments. The sieve analysis is performed to determine the distribution of the coarser, medium, and fine sized particles, and to determine the distribution of the finer particles. The data is being calculated arithmetically and geometrically by using grain size parameters like graphic mean, inclusive graphic standard deviation, inclusive graphic skewness and graphic kurtosis. These parameters reflect the nature of sediments (Table IV.6).

Table: IV.6: Description of Mean, sorting, Skewness and Kurtosis

Location		**Textural Group**	**MEAN**	**SORTING**	**SKEWNESS**	**KURTOSIS**
L1	Yumesamdong (1)	Sand	Fine Sand	Poorly Sorted	Very Coarse Skewed	Mesokurtic
L2	Yumesamdong (2)	Sand	Fine Sand	Moderately Sorted	Symmetrical	Platykurtic
L3	Yumthang Valley	Sand	Medium Sand	Poorly Sorted	Fine Skewed	Very Leptokurtic
L4	Shingba	Sand	Fine Sand	Moderately Sorted	Symmetrical	Platykurtic
L5	Lachung	Sand	Coarse Sand	Poorly Sorted	Coarse Skewed	Platykurtic
L7	Tung	Sand	Coarse Sand	Poorly Sorted	Coarse Skewed	Mesokurtic
L8	Mangan	Sand	Coarse Sand	Poorly Sorted	Very Fine Skewed	Very Platykurtic
L9	Dikchu	Muddy Sand	Very Fine Sand	Moderately Sorted	Coarse Skewed	Mesokurtic
L10	Sirwani	Sand	Coarse Sand	Moderately Sorted	Very Coarse Skewed	Platykurtic
L11	Singtam(1)	Sand	Medium Sand	Poorly Sorted	Fine Skewed	Very Leptokurtic
L12(1)	Singtam (2)	Sand	Very Coarse Sand	Moderately Well Sorted	Very Fine Skewed	Platykurtic
L12(2)	Singtam (3)	Sand	Medium Sand	Moderately Sorted	Very Coarse Skewed	Extremely Leptokurtic
L13	Rangpo	Sand	Very Coarse Sand	Very Well Sorted	Very Fine Skewed	Mesokurtic

L14	Balutar	Sand	Fine Sand	Moderately Sorted	Very Fine Skewed	Platykurtic
L15	Mamring Forest	Sand	Medium Sand	Well Sorted	Fine Skewed	Extremely Leptokurtic
L16	Bhalukhop Forest	Sand	Fine Sand	Moderately Sorted	Very Fine Skewed	Mesokurtic
L17	Melli	Sand	Coarse Sand	Moderately Sorted	Fine Skewed	Platykurtic
L18	Teesta Bazar	Muddy Sand	Very Fine Sand	Moderately Well Sorted	Coarse Skewed	Mesokurtic
L19	Kalijhora	Sand	Medium Sand	Poorly Sorted	Symmetrical	Extremely Leptokurtic
L20	Sevoke	Sand	Coarse Sand	Moderately Sorted	Very Fine Skewed	Very Platykurtic

The textural groups of all the sediments are sand. Its size varies from fine sand to coarse sand. In, sediments from upper stretch from Yumesamdong to Tung north district of Sikkim, the mean shows that sand vary from fine to coarse and sorting varied alternative sequence of moderately sorted to poorly sorted. The skewness of the sediments also changes alternatively coarse to fine and again coarse. Kurtosis of L1 sample is mesokurtic, and L2 to L5 having platykurtic in nature. The sediments from middle stretch of river Teesta shows the presence of alternative coarse and medium sand but abundance of fine sand is increased. The sorting shows increment of moderately sorting of grain from poorly sorted. L9, L10 and L12 (2) shows only very coarse skewed. Remaining samples from this stretch shows fine to very fine skewed. The kurtosis shows the alternate changing of platykurtic and mesokurtic. The sediments from lower stretch of river Teesta shows fine to coarse sequence and poorly sorted grain at L19. Skewness vary from coarse to fine. Kurtosis is mesokurtic, extremely leptokurtic and very platykurtic in nature.

The major mineral present in the sediments are mostly silicate minerals like quartz, orthoclase, garnet, anorthite, calcite, albite and clay mineral i.e. Illite, Illemnite which is determined by X-ray diffraction analysis. The samples were collected from the

Higher Himalaya to Quaternary Siwaliks consisting of the major rock types such as quartzites, gneiss, phyllites, micaceous, schist. The quartz is most abundant mineral present in channel sediments in all three stretches which reveals the dominance of physical weathering. The orthoclase is potassium feldspar and it is also present in all the sediments from Yumesamdong to Sevoke. The abundance of feldspar grains is relatively low in comparison to Quartz minerals. Dominance of silicate minerals in most of the sites may indicate the metamorphic provenance. The garnet is durable mineral and the geological formation- Kanchenjunga and Darjeeling gneiss, Chungthang formation and Gorubathang formation validate the presence of garnet in this region. This may the reason of presence of garnet in river sediments along the stretch. The presence of Illite and Illemnite clay minerals decipher the chemical weathering as well. The illite is present at only four locations-Yumesamdong.1 and 2, Shingba and Mangan. The presence of Ilmenite which is chemically ferrous titanate, $FeO.TiO_2$ is highly resistance to weathering are present in upper and middle stretch of study area. The anorthite is calcium plagioclase feldspar and it is absent in Yumthang, Shingba, Lachung, Singtam1 and 2, Rangpo, and Balutar. The albite is Na- rich plagioclase mineral and it is present in Lachung, Sirwani, Singtam1 and 2; and Bhalokhop forest.

IV.2.3 Provenance Study

Petrographical as well as compositional studies provide information about the tectonic setting of the basin of deposition and associated provenance. Systematic study of sediments reflects the tectonic history of both the source area and framework mineralogy of sediment indicates the climate condition by plotting modal analysis calculated by point counting methods. For plotting Quartz, Feldspar and Lithic fragments are necessary minerals are calculated to 100% (Table IV.7), neglecting all other minerals present in sediments.

Fig. IV.6: Identified minerals at sample locations

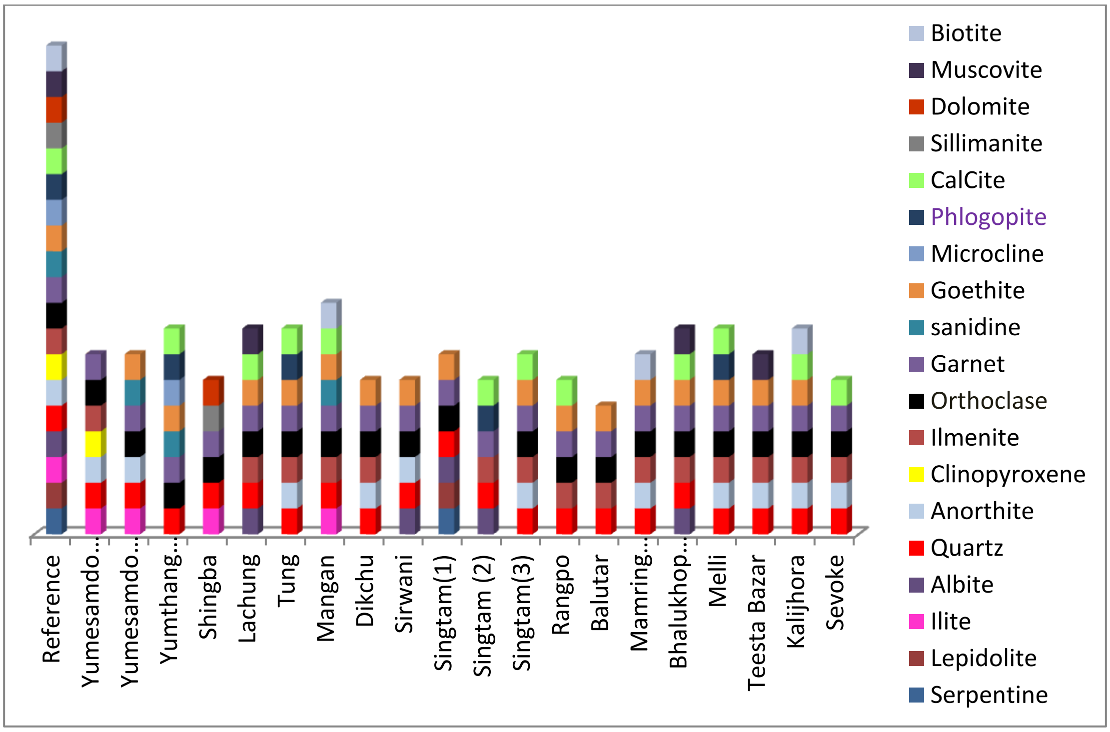


Table IV.7: Modal Analysis Data

Location	Quartz	Quartz (%)	Feldspar	Feldspar (%)	Lithic	Lithic (%)
L1	81	47.37	43	25.15	47	27.49
L2	68	50.75	34	25.37	32	23.88
L3	103	45.58	56	24.78	67	29.65
L4	86	52.76	33	20.25	44	26.99
L5	159	54.45	41	14.04	92	31.51
L7	115	50.00	50	21.74	65	28.26
L8	88	52.07	41	24.26	40	23.67
L9	168	48.98	86	25.07	89	25.95
L10	170	58.22	49	16.78	73	25.00
L11	64	53.78	20	16.81	35	29.41
L12(1)	161	54.39	64	21.62	71	23.99
L12(2)	68	41.46	40	24.39	56	34.15
L13	125	44.01	63	22.18	96	33.80

L14	98	43.75	54	24.11	72	32.14
L15	140	43.75	35	10.94	145	45.31
L16	131	45.17	85	29.31	74	25.52
L17	84	35.29	29	12.18	125	52.52
L18	114	38.78	86	29.25	94	31.97
L19	147	50.17	26	8.87	120	40.96
L20	104	46.64	47	21.08	72	32.29

The petrography study of sediments gives the percentage of quartz, feldspar and Lithic fragments, which is considered to be important minerals because these minerals make study of the origin of grains (provenance)(Fig. IV.7). The presence of feldspar in the sediments shows that physical weathering is more dominant in the region and near to the sediment source. The minimal chemical weathering is generally due to extreme cold environment. As the river originates from high in the Himalaya, minimal chemical weathering is also due to high topographic relief in the source region, so that it is eroded before getting chemically transformed. Lithic fragments also often occur at the base of recent uplift and where rock fragments are plentiful. The presence and dominance of feldspathic arenite and sub-litharenite supports the above fact (Fig. IV.7, Table IV.7).

The percentages of QFL components of all the sediments when plotted in the QFL triangular diagrams has been observed that most of the points of sediments of the study area are dominantly of sub-litharenite and feldspathic arenite (Fig. IV.8a). The compositional plots of sediment show that they were derived from recycled orogen provenance (Fig. IV.8b).

Fig. IV. 7: Petrographical image of the sediments from different location.

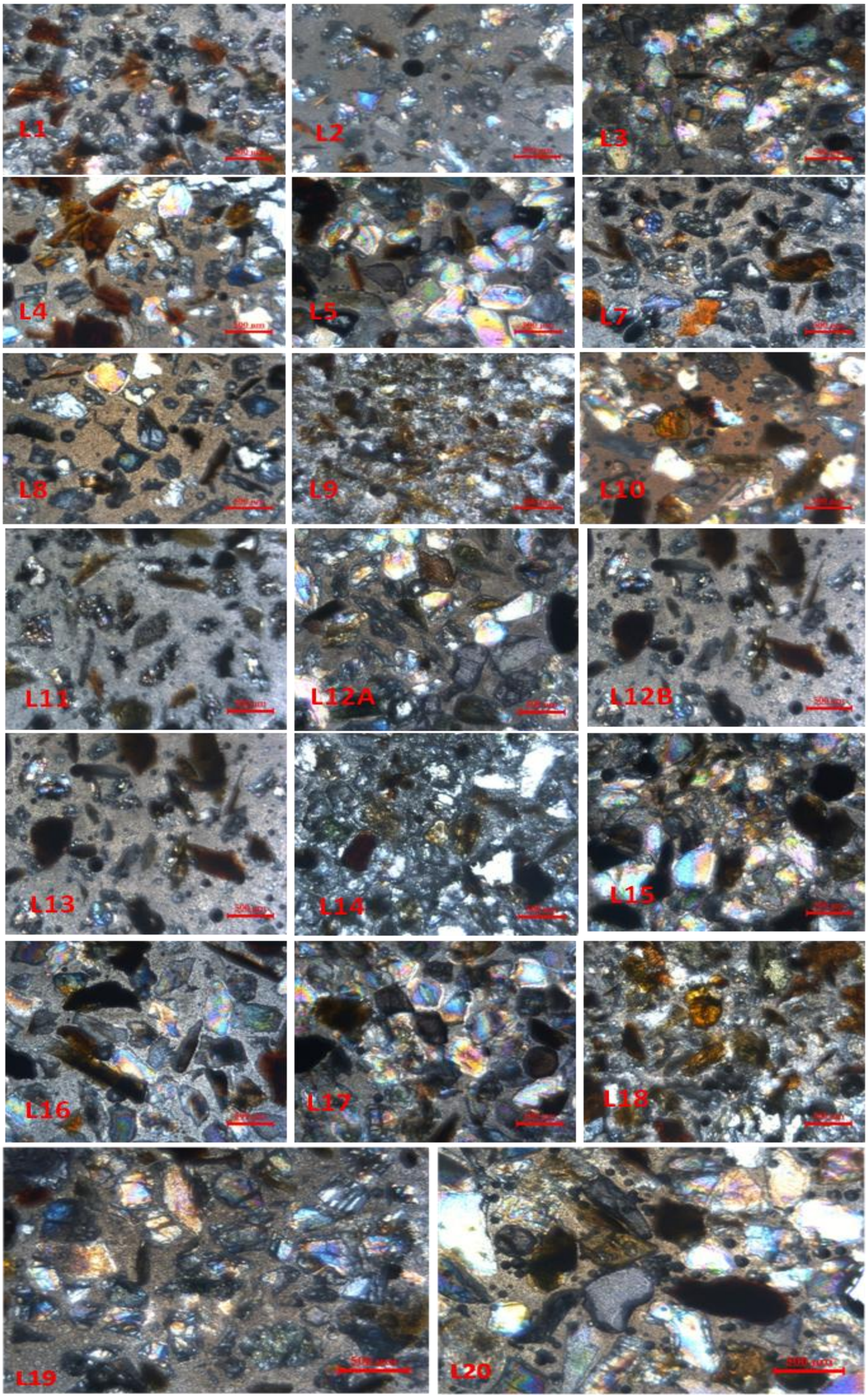
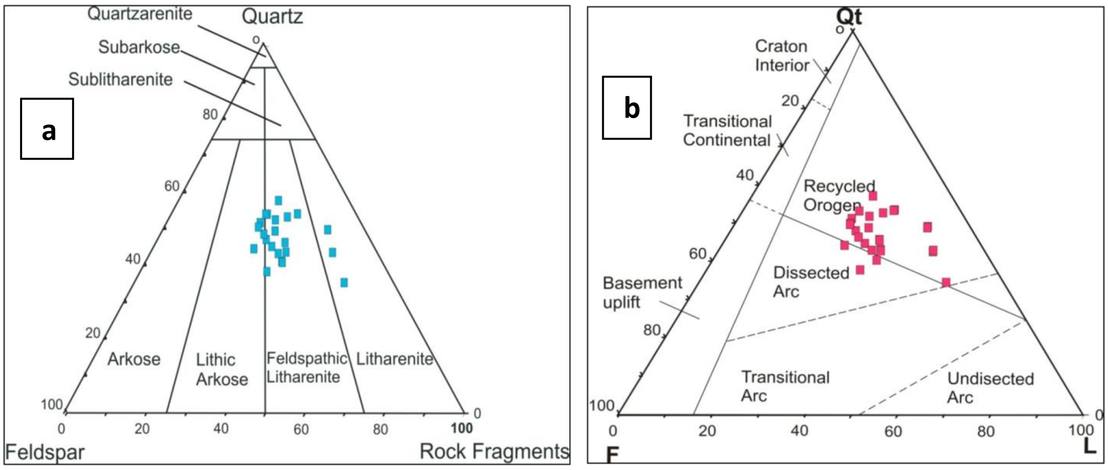


Fig. IV.8: QFL and compositional plots of the sediments



The Teesta river sediments are studied by using grain size analysis, X- ray diffraction and petrography. The grain size analysis shows variation in statistical parameter as- the mean grain size varies from coarse to fine from source area but it shows coarse sand to fine sand. The channel flow deposit constitutes relatively moderately sorted to moderately well sorted sediments and clast-supported gravel with coarse to fine sand matrix. The statistical distribution reveals that sediments are mixed in nature having both mesokurtic and platykurtic distribution. As the sediment transported longer distance sorting increases and grain disintegrate from coarser to finer sediments which is confirmed by sorting and skewness correlation. Therefore, there is a wide variation in sediment characteristics has been observed downstream of river Teesta. This variation may be due to tectonic influences in the area and human interference.

The X- ray diffraction analysis infers major mineral present in the sediments are mostly silicate minerals like Quartz, Orthoclase, Garnet, Anorthite, Calcite, Albite and clay mineral i.e. Illite and Illemnite. The Quartz is most abundant mineral present in channel sediments in all three stretches which reveals the dominance of physical weathering. The presence of Illite and Illemnite clay minerals decipher the chemical weathering as well. The abundance of Feldspar grains is relatively low in comparison to Quartz minerals. Dominance of silicate minerals at most of sites may indicate the metamorphic provenance. The presence of Ilmenite which is chemically ferrous titanate, $FeO.TiO_2$ is highly resistance to weathering are present in upper and middle stretch of study area. Therefore, physical as well as chemical weathering contribute to sediment production.

The petrographic study reveals that the grains are more angularity in the higher altitude region, to sub-angular in lower altitude region. The abundance of quartz grains in channel sediment which is determined by modal analysis advocating both metamorphic and sedimentary source as well. Therefore, lithics are dominating indicates compositionally immature. In addition to the natural processes, the anthropogenic activities such as construction of dams on the river Teesta and frequent landslides in the region significantly affects the variation in sediments characteristics.

Chapter V

Water Discharge and Suspended Sediment Flow Dynamics

Sediment load of a channel depends on number of factors viz. precipitation, discharge, flow velocity, magnitude of human impact, environment and topographical features of the terrain, basin geology and geomorphology, (Delpla et al., 2009; Alexander et al., 2010; Xu, et al., 2012; Darby et al., 2013; Mouri et al., 2013, 2014; Lu et al., 2014). The Himalayan mountain system is considered as world's most erosion prone region (Pandey et al., 1999). Runoff of the Himalayan catchments is greatly influenced by the monsoonal rainfall (Thayyen and Hasnain, 1997; Thayyen et al., 1999) and supra glacial, sub-glacial, lateral moraines are few source areas of sediments (Gurneli and Fenn, 1984). Temperature and precipitation are key controlling factors in amount of discharge and sediment load in the river channel (Wulf et al., 2010; Immerzeel et al., 2013; Lutz et al., 2014; Kumar et al., 2016) in addition with other geomorphological and geological factors. Sediment transport is also dependent on hydrological entities of river channel such as liquid precipitation and discharge (Bookhagen et al., 2005; Szilo and Bialik, 2018; Kumar et al., 2002). Sediment and its composition help understand flow dynamics, geomorphology, hydraulics, siltation in reservoirs (Zhang et al., 2006; Wang et al., 2008; Panwar et al., 2016).

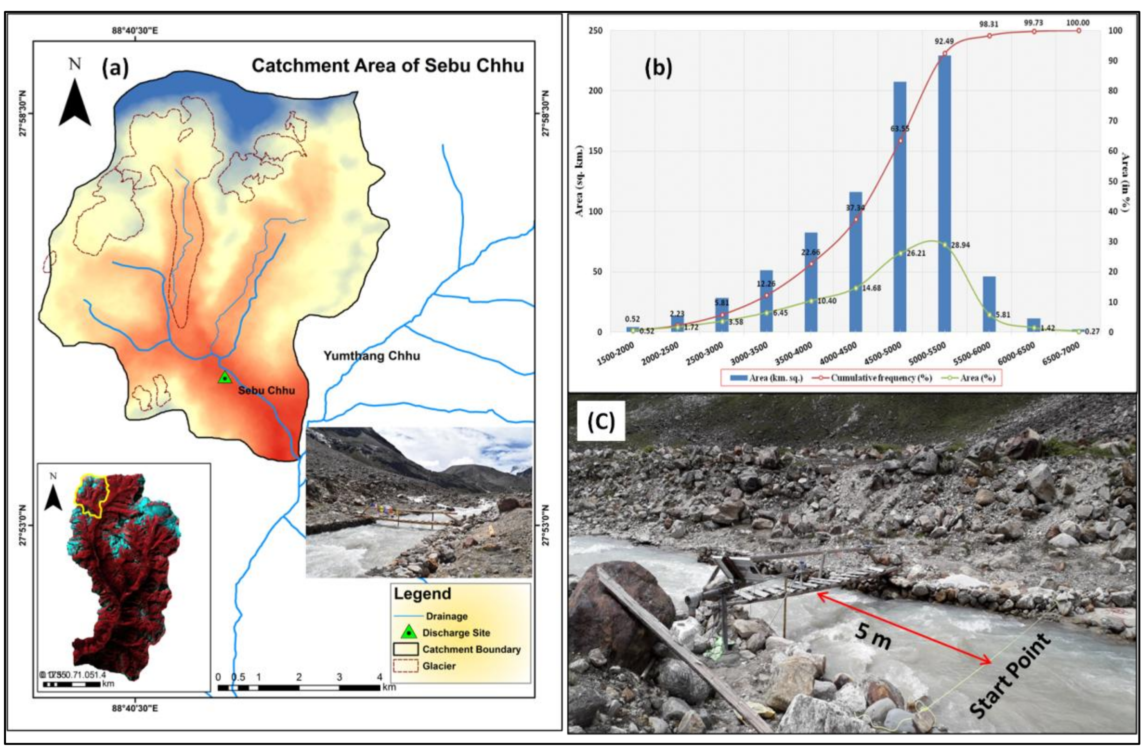
Present study is first attempt to assess the sediment load and discharge in small catchment of *Sebu Chhu* river (48.16 km^2), out of total 11 catchments in the Changme Khangpu basin, during melting season (28th July – 20th August) in 2017 and 2018. The total area of this glacierized catchment is 48.16 km^2 where altitude of the discharge site is at 4684 m a.s.l (27° 54' 59.17" N and 88° 41' 41.78" E). The catchment area covers Changme Khangpu glacier and three other glaciers (Fig. V.1a), which ultimately contribute to the Lachung *Chhu*, a tributary of river Teesta and lifeline for the people in Lachung village.

Months of May, June, July, August and September have been identified as melting season, called summer, while November, December, January and February have been the accumulation season, called winter in the basin. Main objective of this study is to understand pattern of melting of glacier and its contribution to the river discharge and associated suspended sediment loads during ablation season. Quantitative variation in discharge and sediment transport pattern in the *Sebu Chhu* catchment have been assessed to understand the erosional processes in the basin. Impact of diurnal variability of temperature on discharge and sediments load have also been examined. An attempt has also been made to build correlation among different hydrological parameters viz. Discharge (Q), Total Suspended Sediment (TSS), Suspended Sediment load (SSL) and Suspended Sediment Yield (SSY) and its dependence on local temperature to understand the melting pattern and erosional process of catchment.

An appropriate site for discharge measurement was selected in the basin where all the channels of the watershed joined the *Sebu Chhu* river. The discharge point is around 2 km downstream from the snout of Changme Khangpu Glacier and 3 km to 5 km from other glaciers in the basin. The river flow was contained within 6 meters width by constructing embankments on both sides of the channel.

Float-Area velocity method was used to calculate the channel discharge. The discharge measurement has been done from 28th July to 20th August in 2017 and 2018. The channel cross-sectional profile was measured at the start and end day of the season using standard survey technique with the help of a ruler and measuring tape. Depth of the river has been measured at one-meter interval to estimate the cross-section area of the river. The water level of river has been measured using vertically-mounted rod bearing a graduated height measurement scale. Flow length has been taken as 10 meters with discharge bridge as a centre (Fig. V.1c). Channel flow velocity was measured using wooden floats and stopwatch over the flow length of the river and dividing flow length in meters by float time in seconds. The float velocity measurement has been taken three times in a day, called F1, F2, and F3, and then mean value has been considered as F (float velocity in meters per second). The float measurement and water level has been taken on hourly basis from 7.00 am to 6.00 pm and the final mean has been considered for the estimation of discharge for the day. The discharge of the river has been finally calculated using water level, cross-sectional area and the float velocity relation.

Fig. V.1: (a) Sampling site of Sebu *Chhu* glacierized catchment, **(b)** area-altitude distribution of the basin **(c)** discharge site on Sebu *Chhu* river in the Changme Khangpu basin at an altitude of 4684 m a.s.l.



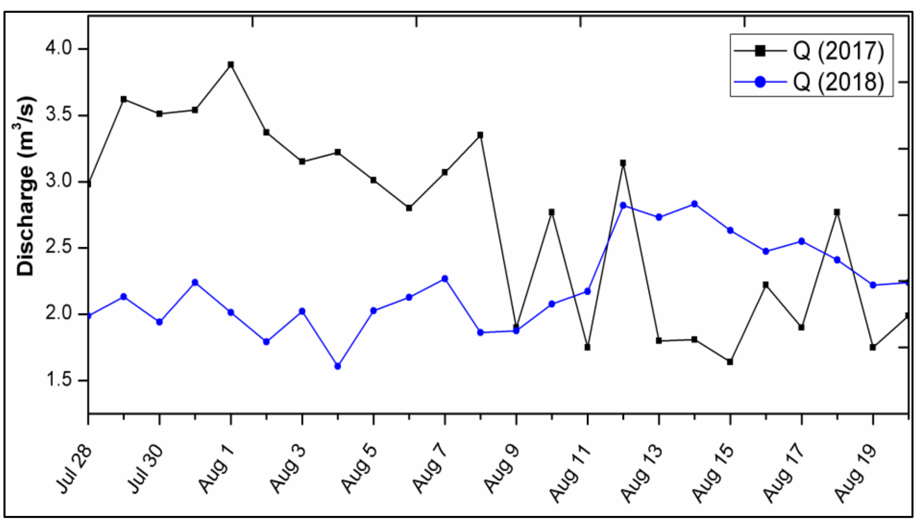
The TSS, SSL, SSY of *Sebu Chhu* catchment have also been measured for the same period. In order to estimate these values, water samples were collected in pre-washed

1000 ml beaker twice a day in the morning (08:00 h) and evening (17:00 h). The water samples have been taken from mid-river with the help of a container placed at 45^o angle until it is filled. This collected water has been allowed to pass through pre-weighed Millipore nylon membrane filters (having 47 mm diameter and 0.2 µm pore size) in a vacuum water filtration unit at the base camp. Nylon filter papers used for filtration were first washed with deionized water to remove the presence of solids during manufacturing process, if any and then dried at 100^o C for 30 minutes in oven and placed in desiccators for 24 hours. The mass of filter papers before use was measured using the Sartorius micro balance (CPA26P) having 2 µgm resolution in the laboratory. After collection of suspended sediments in the base camp, these filter papers were dried and stored in airtight polythene zip bags and were taken to laboratory and placed in a desiccator for 24 hours. The filter papers were again weighed using the same micro balance. The gain in mass of filter paper represents the amount of suspended sediments and then the concentration of TSS has been calculated and expressed in mg/l. SSL has been estimated by multiplying the discharge (l/sec) with TSS and expressed in tones per day. SSY has been estimated by dividing SSL with surface area of the watershed and expressed in tones/ year-km^2. Temperature at the site was also measured using the portable temperature data logger for the study period as there is no weather stations in nearby area. The temperature was taken on hourly basis and then the mean of the same is taken as daily mean temperature for present study.

V.1 Discharge and transportation of suspended sediments

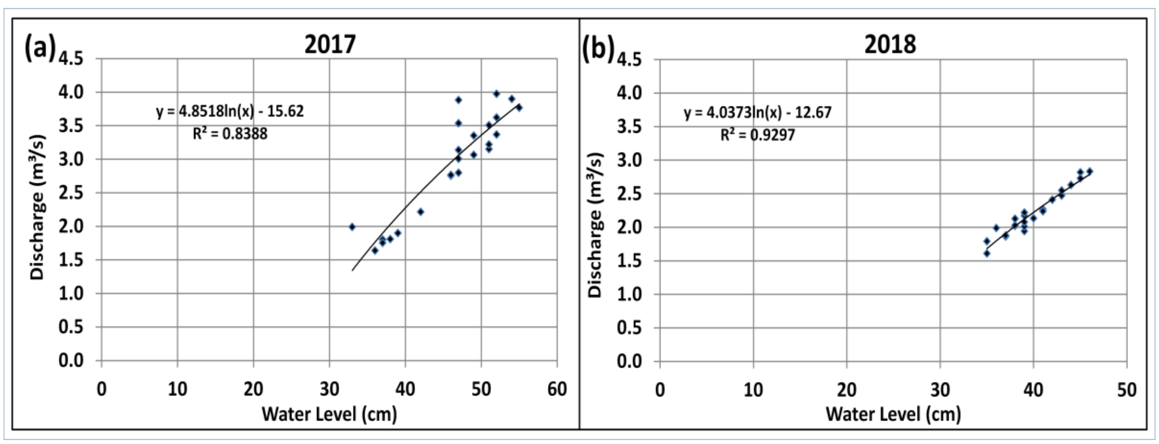
Daily discharge (cu. m/s) during ablation season in the Sebu *Chhu* river catchment have been compiled and a hydrograph has been prepared for 2017 and 2018 (Fig. V.2). It is evident from the analysis that the discharge is relatively lower in 2018 than 2017. The ablation season runoff observed in the Sebu *Chhu* river catchment in 2017 showed a daily average discharge of 2.71 cu. m/s, with maximum average discharge of 3.88 cu m/s on 1st August and minimum average discharge of 1.64 cu. m/s on 15th August. The average discharge in 2018 is found to be 2.21 cu. m/s with maximum average discharge of 2.83 cu. m/s on 14th August and the minimum average discharge is 1.61 cu. m/s on 4th August. It is also observed that total discharge in the basin is always less in the morning than evening for both the years. This difference in the discharge may be because of high rate of melting of snow and glaciers in afternoon. The basin usually receives rainfall in afternoon and weather are relatively clear during morning as according to the field observation. This may be another factor of higher discharge in the evening. A rating curve has been developed for ablation season of the year 2017 and 2018 which shows a very good correlation between water level and discharge (R^2= 0.83 in 2017 and R^2= 0.92 in 2018) (Fig. V.3a, b). This rating curve may be used for estimating the discharge of the river with the help of water level only.

Fig. V.2: Ablation season runoff observed in the Sebu *Chhu* river catchment for two months between 28th July to 20th August, 2017 and 2018.



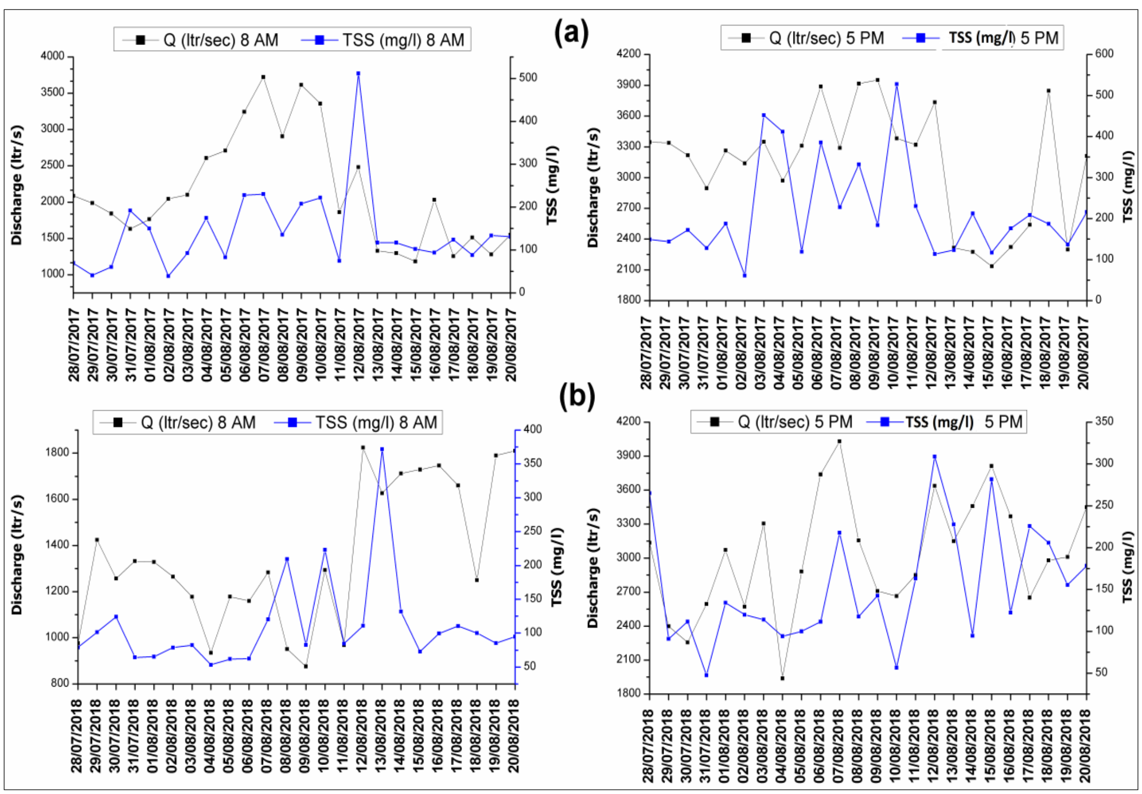
In glaciated basin, rocks, moraines, and debris on and off the glaciers are the primary sources of sediments present in the river (Haritashya et al. 2006; Kumar et al. 2018). Rate of erosion is usually higher in ablation season (Kumar et al. 2018; Shukla et al. 2018), especially in debris covered glaciated region, as the debris in glacier catchment are covered with seasonal snow most of the time in a year. It accelerates the erosion during melting of snow. Higher rate of erosion result in high amount of sediment load in a river that can affect the functioning and life cycle of hydropower projects operating downstream. Therefore, suspended sediments in water released from high altitude has an important role to play in understanding its impact on hydropower generation as well as use of water for people living downstream.

Fig. V.3: Rating curve and correlation co-efficient matrix for August, 2017 **(a)** and 2018 **(b)**.



The analysis of suspended sediment was carried and the mean TSS during 2017 is found to be 226.79 mg/l and that of in 2018 is 144.21 mg/l. Mean TSS is observed to be relatively higher during evening and lower in the morning showing the similar pattern as found for the discharge in both the years (Fig. V.4a, b). High flux of sediment load in the evening is attributed to high rate of erosion due to higher discharge. Morning mean TSS is found to be 142.42 mg/l and 111.28 mg/l in 2017 and 2018, respectively, whereas in comparison, the evening mean TSS is much higher. It is 216.79 mg/l and 153.59 mg/l in 2017 and 2018 respectively. Similar pattern has also been observed in glacierized catchment of the Western Himalaya in the study done by Kumar et al. (2018) and in Tibetan Plateau by Chen et al. (2016), where the discharge showed increasing trend after 1 pm and reached its peak at around 5-6 pm in the evening. Decrease in total amount of discharge from the year 2017 to 2018 suggests decreasing rate of melting in part of ablation season in the catchment area of the basin. This trend can also be supported by the fact that the snow cover has increased in ablation period in the basin especially at the higher altitudes ranging between 4500 m a.s.l and 5500 m a.s.l.

Fig. V.4: a) Morning (8 am) and evening discharge (5 pm) and TSS plot for the year 2017 in the upper Changme Khangpu basin **b)** Morning and evening discharge and TSS plot for the year 2018.



V.2 Discharge (Q), Suspended Sediment Load (SSL) and Suspended Sediment Yield (SSY)

Distribution of diurnal SSL and discharge have been shown in Fig. V.5. Mean SSL in 2017 and 2018 is estimated to be, 672.5 t/day and 293.9 t/day respectively. Mean SSL in the Sebu *Chhu* catchment in peak melting season varied from 15.55 t/day to 109.10 t/day in 2017 and 10.21 to 70.75 t/day in 2018 (Fig. **V.**5a, b) during the period of observation. Daily distribution of the two melt seasons shows that SSL increases with increase in discharge at the gauging site, however, the discharge is not showing much variation as compared to SSL. Mean SSL in the two-consecutive melt seasons in 2017 and 2018 is estimated to be 55.87 t/day and 28.39 t/day, respectively. Diurnal trend also shows that discharge and sediment load was higher at the beginning of observation period and reduced at the end in 2017, whereas the pattern was just converse (Fig. V.5a, b) in 2018.

Suspended sediment flux and meltwater discharge record in the Indian Himalayan Region (IHR) is lagging because of inaccessibility at higher elevations. However, studies during last few decades have reported many researches from different regions including the Changme Khangpu Glacier in the Eastern Himalaya (Puri and Swaroop 1995; Puri 1999; Singh and Ramasastri 1999; Singh et al., 2006; Raina 2009; Kumar et al., 2014; Singh and Ramanathan 2015; Singh et al., 2016; Singh and Ramanathan 2017). The study of the Changme Khangpu Glacier (4.5 km^2) reports that mean daily discharge and SSL were approximately 0.19 m^3/s and 18 t/day, respectively. Physical Weathering Rate (PWR) was found to be1460 t /km^2 -$year^1$. However, mean value of Q, SSL and SSY (also called PWR) for two years were found to be 2.46 m^3/s, 42.13 t/day and 319.31 t/km^2-year respectively in Sebu *Chhu* glacierized catchment having an area of 48.16 km^2 in present study.

The scatter plot between TSS-Q and SSL-Q for the study period shows a good correlation matrix between the two components in 2017 and 2018. With increase in discharge also increases the SSL in the catchment (R^2 = 0.70 and R^2 = 0.65) and shows much stronger relation as compared to the TSS-Q correlation matrix (Fig. **V.**6a, b). Similar kind of pattern in the Western as well as in other parts of the Himalaya was observed, where, the TSS is higher as compared to its SSL against discharge in glacierized basin (Hallet et al., 1996; Hasnain and Thayyen, 1999; Chen et al., 2016; Kumar et al., 2018). According to some studies, discharge is higher and it peaks in the month of July-August as compared to rest of the months of a year (Srivastava et al., 1999; Kumar et al., 2018; Singh and Ramanathan, 2018). Matrix between discharge and SSL clearly indicates that the sediment flux during part of ablation season exports large concentrations with high meltwater discharge.

Mean diurnal SSY in the basin during the study period was 423.45 t/year-km^2 in 2017, which reduced to 215.18 t/year-km^2 in 2018. Maximum SSY is 826.85 t/year-km^2 and 536.17 t/year-km^2, whereas minimum yield was estimated to be 117.83 t/year-km^2 in 2017 and 77.40 t/year-km^2 in 2017 and 2018, respectively (Table V.1). It reveals that the physical weathering rate in the catchment area was much higher in August 2017 as compared to the same period in 2018. On the other hand, this weathering rate of sediment was much higher in the earlier study by Puri (1999), which was conducted on Changme Khangpu glacier having estimated SSY ~1460 t/year-km^2. Due to long gap in study, it is difficult to build relationship between the recent and earlier study. Therefore, long term assessment of SSY is required in order to address this inconsistency. However, recent study suggests that physical weathering rate and sediment flux in the Sebu *Chhu* river has decreased from 2017 to 2018.

SSY in Sebu *Chhu* catchment is higher as compared to some of the Karakoram and Western Himalayan glaciers- Chandra-Bhaga basin, Nubra basin (Hodgkins et al., 1997, 1999; Bhutiyani 2000; Singh et al., 2015, Kumar et al., 2018). However, highest SSY is reported from Central Himalayan glaciers and in a few glaciers from Hunza basin, Karakoram (Collins 1996, 1998; Singh et al., 2003; Haritashya et al., 2010; Srivastava et al., 2014; Arora et al., 2014; Singh et al., 2014; Kumar et al., 2016). These variations in different parts of the Himalayan region may be because of different climatic regime, bedrock lithology and meteorological influences in these regions (Bhutiyani 2000; Singh et al., 2016). SSY is influenced by seasonal snow cover and other meteorological conditions over the glacier (Collins 1989, 1990; Kumar et al., 2016, 2018).

Fig. V.5: Daily diurnal variation in melt-water discharge and SSL for the part of ablation season in August 2017 **(a)** and 2018 **(b)**.

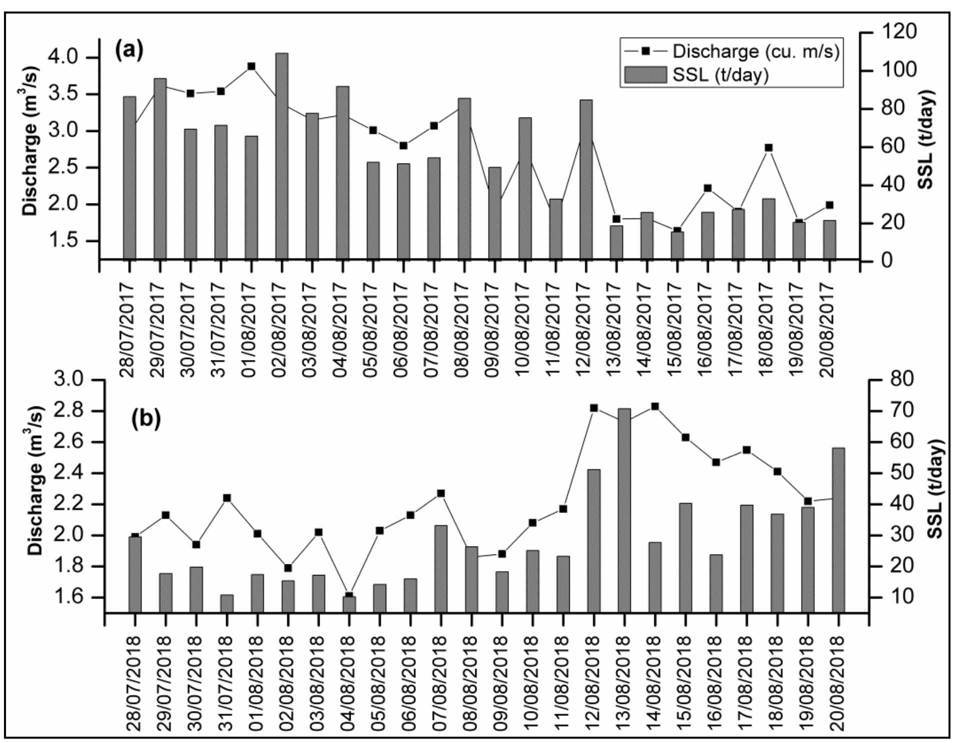


Fig. V.6: Scatter plot between discharge and TSS & discharge and SSL for the year 2017 (**a**) and 2018 (**b**) for a part of ablation season.

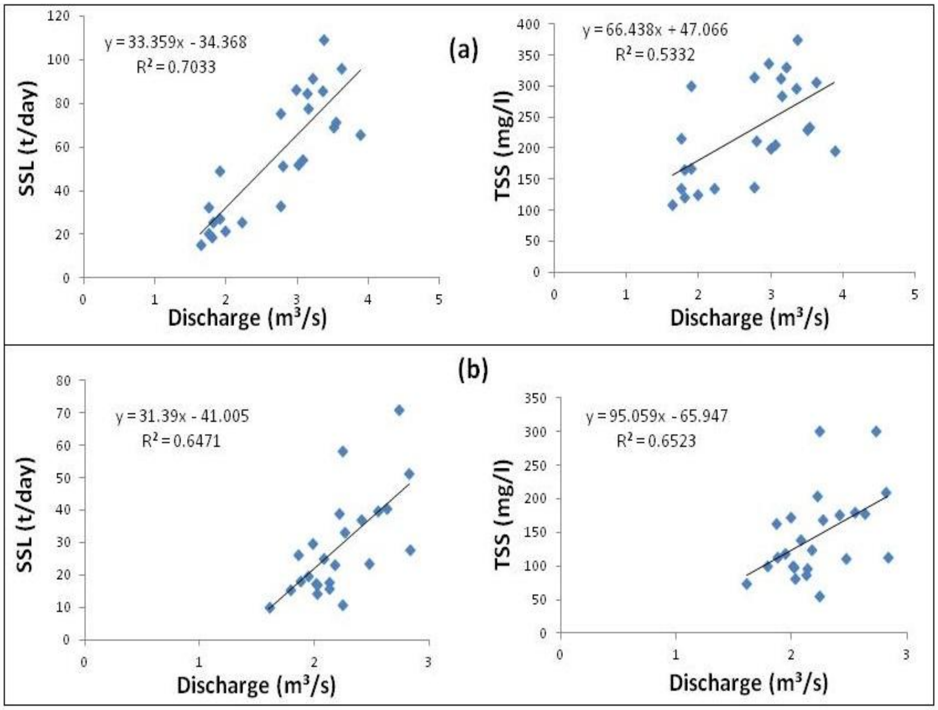


Table V.1: Mean, minimum and maximum TSS, SSL and SSY of Sebu *Chhu* catchment for year 2017 and 2018 ablation seasons.

2017	**TSS (mg/l)**	**SSL (t/day)**	**SSY (tonnes/ year km^{-2})**	2018	**TSS (mg/l)**	**SSL (t/day)**	**SSY (tonnes/ year km^{-2})**
Min.	109.80	15.55	117.83	**Min.**	55.80	10.21	77.40
Max.	374.80	109.10	826.85	**Max.**	300.31	70.75	536.17
Mean	226.79	55.87	423.45	**Mean**	144.21	28.39	215.18

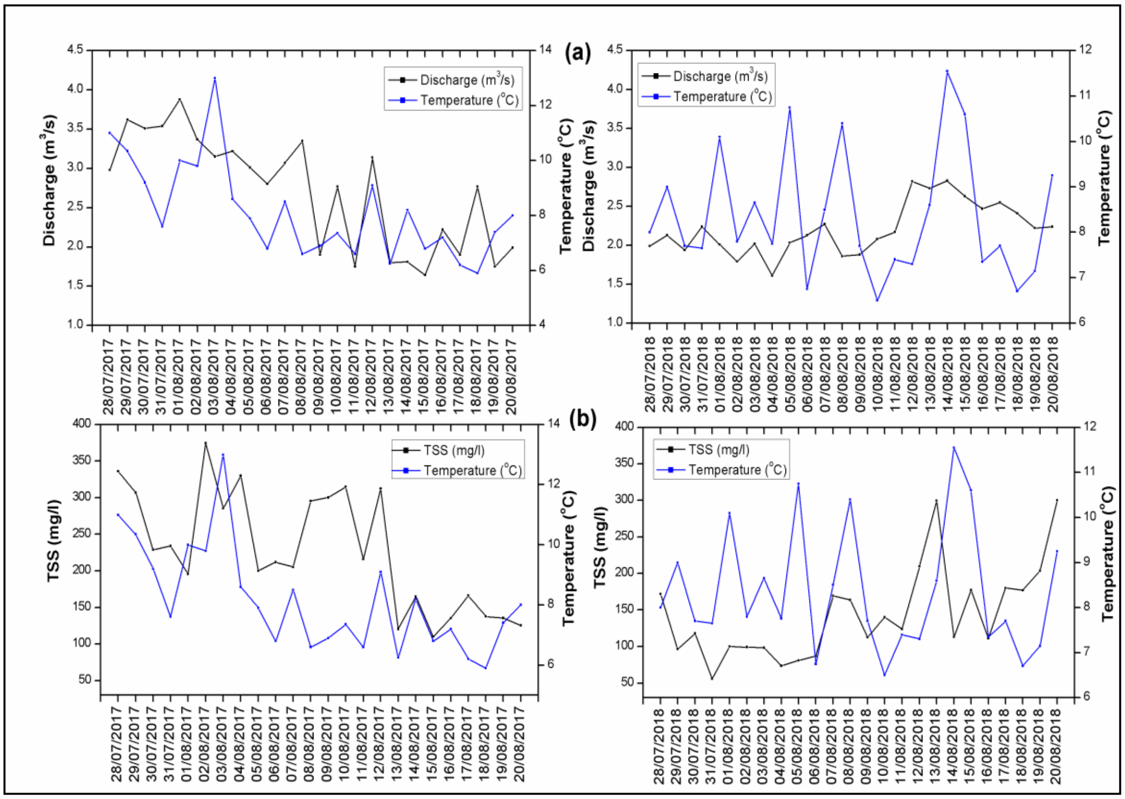
V.3 Temperature and suspended sediments transportation

Local temperature shows a good correlation with discharge as well as TSS. (Fig. **V.**7 a, b) similar to studies conducted in the Western and Central Himalaya (Mouri et al., 2014; A. Kumar et al., 2018; Kumar et al., 2018; Singh et al., 2018). It has been observed that the mean discharge for 2017 and 2018 follow similar trend of temperature with a few exceptions. Increasing temperature lead to increase in stream flow ultimately increasing sediment flux into the river with few exceptions where other than temperature and precipitation, the geology and snow melt also leads to sediment supply in the catchment. Sometimes discharge is higher even in low temperature condition which is due to precipitation events on the same day in the catchment which is in observation. High precipitation resulted in high stream discharge and eventually high TSS and SSL. The results also substantiate that the stream flow in a glacierized basin is majorly connected with temperature and precipitation. The TSS may increase in exponential alteration with a small variation in temperature and the sediment concentration in downstream areas is directly correlated with discharge (Srivastava et al. 2014 and Kumar et al. 2018).

Transportation of suspended sediments in Sebu *Chhu* catchment is mostly influenced by its geology, seasonal snow cover and meteorological conditions over the glacier. The sub-basin of Changme contains 4 glaciers and the largest glacier Changme Khangpu is highly debris covered. Nature of glacier also affects flow of sediment load and its pattern in a river. It was found that the SSL and temperature are correlated to each other. But SSL supply to the Sebu Chhu river can be the result of melting in ablation season as well as due to higher mass movements and weathering in upper part of the basin. Entire basin is highly prone to snow avalanches and debris/ rock falls starting from higher altitudes up to the lower most part of the basin (1550 m a.s.l), thus increasing the TSS in the river basin.

The dynamics of flux of suspended sediment concentration, its load and total annual yield (the weathering rate) in the Sebu *Chhu* glacier catchment and its relation to the discharge variation for part of the ablation season in 2017 and 2018 has been studied. The total discharge in Sebu *Chhu* catchment is always less in the morning than evening in both the years under study. High discharge in the evening may be because of high rate of melting of snow and glaciers and relatively high precipitation in the afternoon. A good correlation was observed between discharge and water level.

Fig. V.7: Relationship between air temperature and discharge **(a)** and temperature and total suspended sediment **(b)** for the ablation season of 2017 and 2018.



A good correlation, R^2= 0.7, R^2= 0.6, is also found between sediment load and discharge in the catchment area in 2017 and 2018, respectively. Positive relation between discharge and SSC and SSL was also reported from other parts of the Himalaya, (Hasnain et al., 1989; Hasnain and Chauhan 1993; Dimri 2004; Srivastava et al., 2014; Singh et al., 2015, 2018; Priya et al., 2016; Mir et al., 2017; A. Kumar et al., 2018; Kumar et al., 2018). The SSL in 2017 shows a rising trend during the start of ablation and decrease at the end but the trend is just reverse in year 2018. Diurnal estimated TSS shows a good relation with discharge while SSL shows much significant relationship with the melt-water discharge in the catchment. SSL and SSY in the study area have shown a decreasing trend from

2017 to 2018 in ablation season. Mean value of Q, TSS, SSL and SSY (also called PWR) for ablation season of 2017 and 2018 were found to be 2.46 m^3/s, 185.50 mg/l , 42.13 t/day and 319.31 t/km^2-year respectively. Diversity in local weather pattern and climatic regime as well as the geology and bedrock of the area are other factors that influence the amount of weathering and total sediment flux in a season. Due to limited data availability for the Eastern Himalayan region, trend of sediment and discharge is difficult to estimate despite being of high importance for downstream areas. Therefore, long-term observation of temporal variation of hydrological characteristics (Q, TSS, SSL and SSY) in a basin is of utmost importance for settlements downstream and also for management of hydropower projects in the region.

Chapter VI

Snow Cover Estimation

Snow covers ~ 40% of the Earth's land surface during Northern Hemisphere winter and this makes the areal extent of snow and albedo as an important component of earth's radiation balance (Foster et al., 2003). Also, snow plays an important role in earth's climate regulation being an element of the water cycle, maintaining Cryospheric regime and a thermal insulator (Goose et al., 2010; Ming et al., 2014). The Himalaya 'abode of snow' has many large rivers originating and regulating by the snow and glacier melt. The seasonal change in area of snow affects the stream flow for the rivers originating high in the Himalaya (Kaur et al., 2009; Kumar et al., 2019). All the rivers originating from higher Himalaya receive almost 40-50 % of annual snow and glacier melt run-off (Agarwal et al., 1983, Jeelani et al., 2012; Armstrong et al., 2019). Changes in precipitation phase and increase in air temperature can lead to early snowmelt and affect stream runoff pattern (Rongo et al., 2000; Kulkarni et al., 2002; Pratap et al., 2019).

The snow and melt run-off study are vital aspects for avalanche forecasting, environmental impact, estimating potential of mini and micro hydro-power plants and to understand the hydrology for water resource management (Lutz et al., 2014; Immerzeel et al., 2009; Wang et al., 2010; Thayyen and Gergon 2010; Chu, 2018). Heavy seasonal snow also affects transport and communication as well as daily life; changes in snow precipitation impact on water provision, agriculture, tourism and recreational activities. To simulate and forecast the daily stream-flow in snow covered and glacierized basin, the accurate data on snow cover area (SCA) is of utmost importance (Martinec 1975; Mir et al., 2015a). In India, the perennial rivers in Himalayan region are delivered by snow melt and glacier melt runoff (Singh and Singh 2001; Krishna 2011; Lutz et al., 2014). The contribution of snow to different aspects shows that it is very useful for efficient series monitoring of seasonal snow in the Himalaya.

Despite importance of snowmelt water contribution to volumes of the Himalayan rivers, its characteristics are less understood due to complexities of processes involved in snow hydrology as well as owing to lack of hydro-meteorological data in the high-altitudes (Prasad and Roy 2005; Miller et al., 2012). For instance, the seasonal snowline descends to an altitude of 2000 meters in the Western Himalaya by February (Jain et al., 2010). As the snowmelt commences in March, the snow line starts receding upwards and by the end of June it reaches to an altitude of 5500 meters (Gaddam et al., 2016; Pratap et al., 2019). In terms of snowmelt runoff estimation, SCA and temperature are important parameters of estimation and can be obtained from both remote sensing data and meteorological data (Poon 2004; Alam et al., 2011; Abudu et al., 2012). Remote sensing products such as MODIS, AWiFS, Landsat and recently Sentinel-2 can provide an easy tool to observe seasonal, annual and decadal changes in SCA (Racoviteanu et al., 2008). MODIS products offer the best potential for snow mapping on regular basis with respect to temporal and spatial resolution and in terms of accurate data availability (Hall et al., 2002; Hall et al., 2007; Parajka and Bloschl, 2008; Mir et al., 2015b).

Considering importance of snow as water resource and environmental component, its variation plays an important role in the spatial and temporal distribution in the basin. It is also an indicator of environmental change. Avalanche and snow induced disaster in winter seasons can also be one of the major problems in the region. Therefore, the present study has been done with the purpose to relate variation of SCA with variable temperature on a regional and local scale.

Satellite images for the distribution of snow cover in Changme Khangpu Basin (CKB) of North Sikkim has been analyzed. Altitude of the basin ranges from 1540 to 7000 meters a.s.l and occupies an area of 792.17 km^2. About 70 % of the basin area is located above 3000 meters a.s.l which does not exceed 45^o slope. The total slope area below 45^o is around 637.28 km^2. The basin has many small streams originating from single to a group of glaciers. All these streams merge to form Lachung *Chhu* which is one of the prominent tributaries of the Teesta River (Fig. VI.1). The area receives average annual rainfall between 347 mm and 2400 mm; it receives precipitation in the form of snowfall as well in winters. The summer is between May to July and winter from November to February because the ablation and accumulation pattern in Sikkim is different as compared to other parts of the Himalaya (Basnett et al., 2012; Basnett and Kulkarni 2019). The air temperature varies from 9^o C to 25^o C in summer and -10^o C to 9^o C in winter. Snowmelt runoff is one of the primary inputs of river discharge and is the major source of water supply in these regions. Though seasonal snow cover has noticeably less volume of water as compared to glacier ice melt but is economically more important as it is also considered as a rich water resource downstream, downstream erosion and for the generation of hydroelectric power in Chungthang station (1550 m a.s.l) (Fig. VI.1).

VI.1 Data and Method

The data from different sources has been taken and analyzed for the snow cover estimation in the present study area between 2002 and 2019 and the outputs were compared with existing studies. The data used for snow cover mapping is mainly the MODIS 8-day composite snow cover products from Terra (MOD10A2) and is an eight-day composite of MOD10A1 (daily snow product) to show maximum snow extent. The MODIS snow cover products are generated using a global snow cover extraction algorithm available on 500 meter spatial resolution. Temporal resolution of MODIS varies as it gives daily snow extent, 8-day composite, and monthly snow extent as an end product. The snow products containing the tile number 'h25v06.006', were downloaded from the NSIDC website (https://n5eil01u.ecs.nsidc.org/MOST/MOD10A2.006/), for the period between 2002 and 2019. For studying the influence of temperature on monthly, annual as well as seasonal snow cover area, the weather data (historical weather simulation data) has been obtained using history+ from meteoblue site which is based on the local model for India having a resolution of 12x12 km (https://www.meteoblue.com/en/historyplus). The data has been obtained for two stations namely- Lachung (2800 m a.s.l) and Yumesamdong base station (4800 m a.s.l).

The processing of the data includes the re-projection of 876 MODIS snow products from Sinusoidal projection to UTM projection and image rectification. As the resolution of MODIS files is 463.3 m, all the files have been resampled to 500 m in Arc Map 10.2 to maintain the uniformity and later on the Area of Interest (AOI) has been extracted from MODIS product. The average monthly mean SCA was estimated by taking the average value of scenes of that particular month. Further, the monthly, seasonal and annual snow cover extents for the year 2002-2019 have been taken into consideration to understand the behavior and changing pattern of snow cover in the basin. The seasons have been divided into two parts- the ablation (May-September) and accumulation (November-March). The month of April is considered as springs in the basin where the area above 4500 m a.s.l is generally snow covered. The interpretation used for snow cover was based on standard MODIS snow products integer value 200 which represents snow on the imageries and the detailed flow-chart methodology for estimation of SCA using MODIS is shown in Fig. (VI.2).

Fig. VI.1: Changme Khangpu basin in Sikkim, India. Background generated using ASTER GDEM having 30 m resolution and the elevation ranges from 1500 to 7000 m a.s.l.

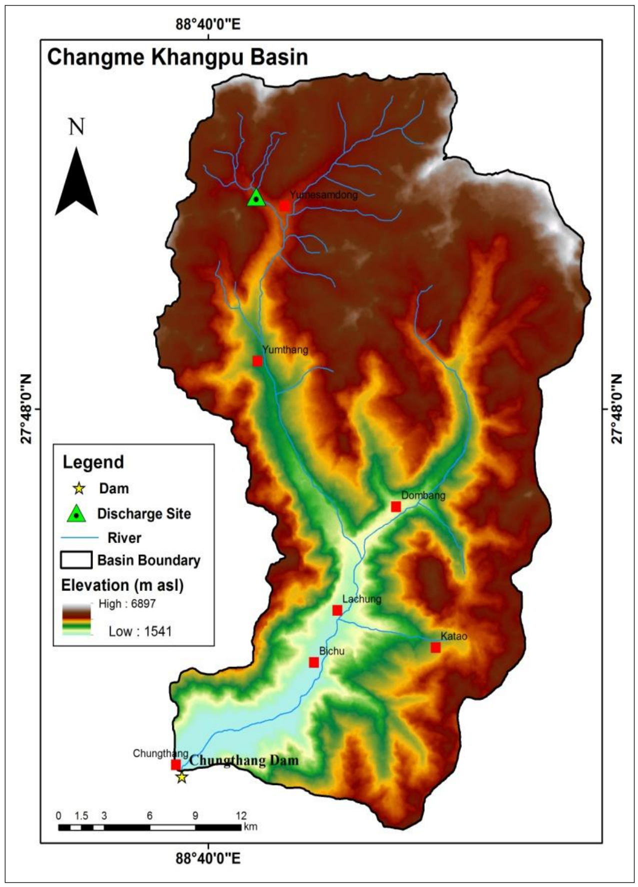
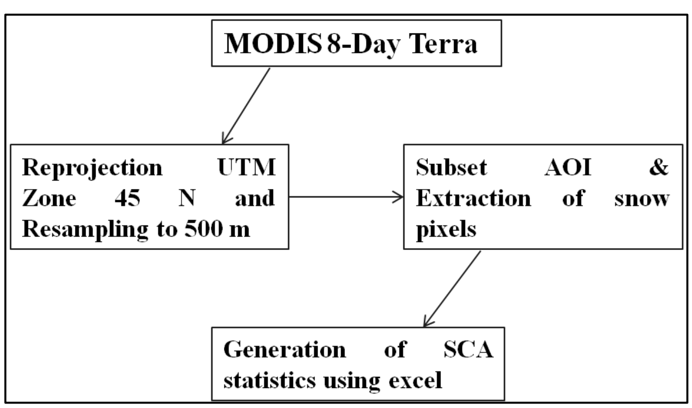


Fig. VI.2: Method opted for the extraction of the snow-covered area (SCA) from MODIS 8-Day terra data.



VI.2 Results

The study was done to estimate the different aspects of snow cover variation and fluctuation both monthly and annually. The seasonal disparity in SCA has also been studied for understanding the melt contribution of seasonal snow in the basin, including the altitudinal distribution of SCA which shows a wide range of deviation between the low altitudes which contains the seasonal snow cover and the permanent snow covered parts of the basin.

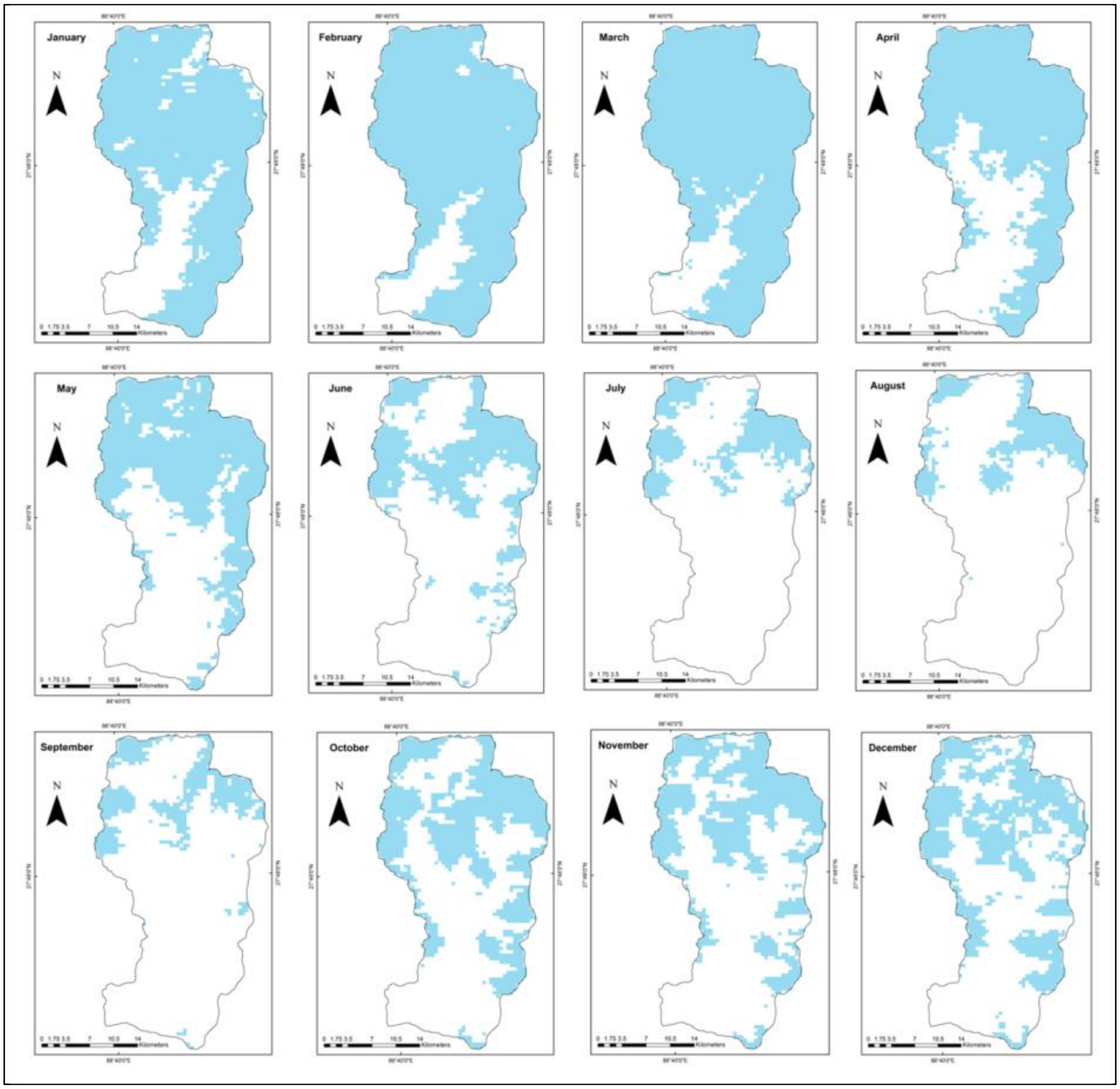
VI.2.1 Snow Cover Distribution in Changme Khangpu Basin (CKB)

CKB is characterized with glacierized and snow cover area, where the snow and ice melt contribute significantly to the downstream river. Two moisture sources dominate in the region with a higher amount in winter from western disturbances (WD) and also from Indian summer monsoon (ISM) during the summer period. Our results on SCA assessment during 2002-2019 show the maximum extent in February and March, while it depleted to a minimum during July and August (Fig. VI.3). Despite the maximum SCA in winter months, summer contributes large amount of precipitation in the higher attitude as found small increase in SCA during July and August.

VI.2.2 Monthly and Annual Snow Cover Trend During 2002-2019

Monthly snow cover between January and December across the almost two decades showed maximum snow cover extent in February and March with 85.67 ± 12.98 % and 81.49 ± 11.59 %, respectively (Table VI.1). After March with the onset of summer, the SCA starts depleting gradually and reaches its minimum (~40 %) in July. Subsequent to maximum depletion of SCA at the end of July and August, it starts increasing with the onset of post-monsoon to the winter season. From October to December, the SCA sustained at the fixed transient line as the snowfall occurs only at the higher altitude region.

Fig. VI.3: Mean monthly composite records of snow-covered area (SCA) extent in the Changme Khangpu basin from 2002 to 2019.



The mean monthly SCA of 18 years (2002-2019) suggests that snow cover reached its maximum in February to 85.66 ± 12.98 % (678.62 km^2) and minimum in July 35.52 ± 5.83 % (281.42 km^2). The mean monthly snow depletion curve suggests that snow starts accumulating from October and keeps on increasing until the month of February-March (Fig. VI.4a). From March end or April onwards, it starts decreasing with the lowest snow cover area in June 46.70 ± 5.23 %, July 35.52 ± 5.83 % and August 39.56 ± 6.52 %, respectively. The rate of SCA decline is linear from March onward, but found a slight crimp during June, where SCA depletion has flattened. Similarly, the SCA results show a small decline in November after rapid increase in August to October (Fig. VI.4a).

The annual trend in snow cover is showing a slight decreasing trend in extent of SCA between 2002 and 2019 (Fig. VI.4b). The highest SCA was observed in 2003, 538.39 ± 49.53 km^2 (67.46 ± 9 %) and lowest in 2017, 442.60 ± 42.25 km^2 (55.87 ± 7.1 %) (Fig. VI.4b, Table VI. 2). In CKB, the mean annual SCA from 2002 to 2019 estimated to be 62.08 % ± 10.15 % (491.45 ± 90.01 km^2). The maximum and minimum SCA was in 2003 with 67.46 % ± 10 % (534.39 ± 49.53 km^2) and 2017 with 54.21 % ± 9.1 % (429.45 ± 35.25 km^2), respectively. The inter-annual variation in trend line shows negative trend of 3.81 ± 2.05 % in SCA from 2002 to 2019 (Fig. VI.4c).

Table VI.1: Mean monthly and annual SCA (%) in CKB for two decades with mean monthly and annual snow cover area between 2001 and 2019.

	Jan.	**Feb.**	**Mar.**	**April**	**May**	**June**	**July**	**Aug.**	**Sept.**	**Oct.**	**Nov.**	**Dec.**	**Mean**
2002	83.08	87.75	88.96	75.03	55.18	57.34	40.62	40.18	47.08	74.92	67.25	75.19	66.05
2003	82.36	92.84	89.04	80.00	47.25	51.10	44.74	40.53	53.45	72.76	72.62	82.82	67.46
2004	89.09	86.35	78.28	59.41	35.46	44.21	38.26	37.73	58.62	68.91	79.63	76.68	62.72
2005	90.73	90.79	86.42	60.41	47.49	49.32	32.47	35.63	45.03	75.97	67.97	64.43	62.22
2006	57.96	80.56	89.50	80.75	55.10	50.85	34.26	38.06	52.96	76.17	78.22	74.54	64.08
2007	82.08	92.32	88.84	79.58	48.31	40.53	35.84	42.59	44.79	62.37	72.51	58.61	62.36
2008	71.92	91.26	83.19	63.08	46.20	43.04	31.51	41.38	64.50	70.34	64.57	63.98	61.25
2009	80.14	87.32	79.18	72.05	59.61	34.95	39.67	40.28	58.10	67.97	69.59	67.71	63.05
2010	67.53	87.71	79.99	49.03	52.84	47.18	36.23	32.41	40.55	74.88	66.88	62.70	58.16
2011	79.77	88.54	83.24	77.63	61.02	51.91	40.38	33.84	49.14	81.15	75.67	72.26	66.21
2012	88.91	86.75	86.32	77.57	47.04	43.23	41.80	39.36	62.05	65.79	57.06	73.28	64.10
2013	73.62	88.90	82.80	65.22	55.58	49.22	36.13	37.14	33.56	82.35	77.83	76.16	63.21
2014	78.95	88.66	85.98	73.20	64.47	43.36	31.56	39.36	42.87	63.35	47.02	81.65	61.70

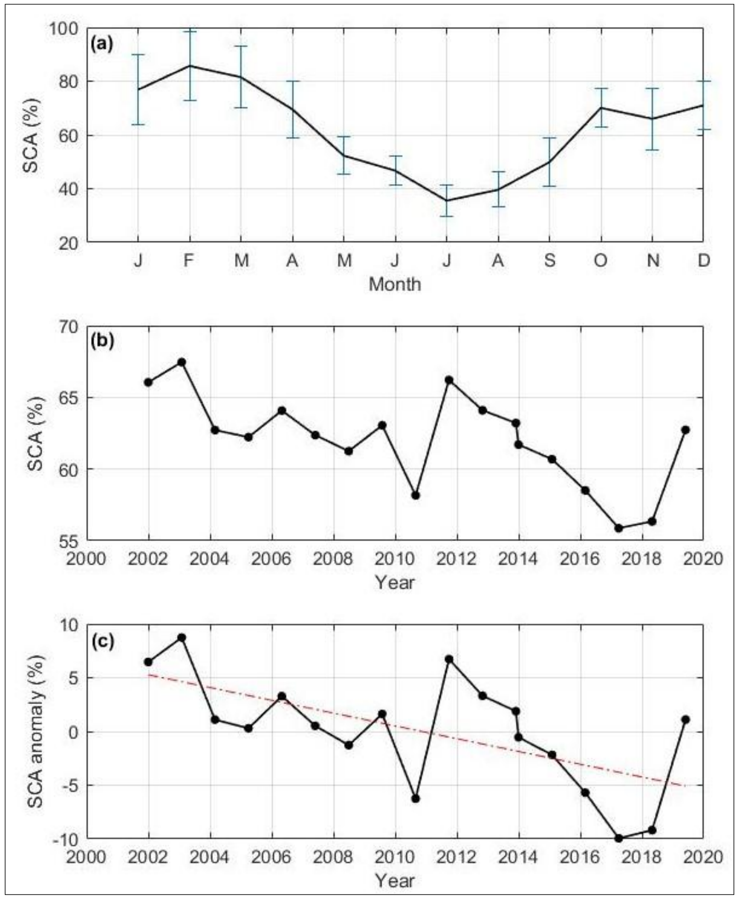
2015	84.26	91.43	80.59	78.38	53.93	41.56	31.24	39.11	39.16	67.71	59.91	60.94	60.69
2016	85.51	83.49	81.35	70.58	54.65	46.64	23.54	36.13	56.64	59.03	50.10	54.40	58.51
2017	83.75	81.26	88.34	64.45	54.02	45.60	40.17	36.96	37.66	47.49	34.95	35.88	54.21
2018	46.83	89.81	76.17	67.15	50.00	45.64	24.01	43.02	46.71	59.12	53.36	74.28	56.34
2019	88.92	92.33	88.73	77.21	60.15	49.03	35.29	32.81	42.27	63.10	46.04	76.86	62.73
Mean	**78.64**	**88.23**	**84.27**	**70.60**	**52.68**	**46.37**	**35.43**	**38.14**	**48.62**	**68.52**	**63.40**	**68.46**	**61.95**

Source: Computed on the basis of MODIS snow cover products

Table VI.2: Maximum and minimum snow covered area (SCA) in the Changme Khangpu Basin (2002 to 2019)

Year	Maximum SCA (%)	Month	Area (km^2)	Minimum SCA (%)	Month	Area (km^2)
2002	88.9	March	704.69	40.1	August	318.31
2003	92.8	February	735.42	40.5	August	321.06
2004	89.0	January	705.75	37.7	August	298.88
2005	90.7	February	719.19	32.4	July	257.19
2006	89.5	March	709.00	34.2	July	271.38
2007	92.3	February	731.33	35.8	July	283.94
2008	91.2	February	722.96	31.5	July	249.63
2009	87.3	February	691.69	34.9	June	276.88
2010	87.7	February	694.81	32.4	August	256.75
2011	88.5	February	701.35	33.8	August	268.06
2012	88.9	January	704.31	39.3	August	311.81
2013	88.9	February	704.21	33.5	September	265.88
2014	88.6	February	702.35	31.5	July	250.00
2015	91.4	February	724.31	31.2	July	247.50
2016	85.5	January	677.38	23.5	July	186.44
2017	88.34	March	648.06	34.95	November	278.81
2018	89.8	February	711.48	24.0	July	190.17
2019	92.3	February	731.38	32.8	August	259.91

Fig. VI.4: Snow-covered area during 2002-2019, (a) monthly mean SCA and error associated with the SCA estimation (b) mean annual SCA and (c) snow cover area anomaly (%) snow depletion curve between 2002-2019.



VI.2.3 Seasonal Snow Cover During 2002-2019

Years are divided into two seasons namely the ablation period (i.e. May to September, MJJAS) and accumulation period (i.e. from November to March, NDJFM) so as to work out the seasonal snow cover extent in the basin. The SCA in accumulation period found to decreasing, while it shows an increasing trend in ablation period (Fig. VI.5a). During accumulation period, the estimated mean SCA was 75.26 ± 5.21 %, around 1.68 times higher than the mean SCA of ablation period (44.78 ± 3.11 %) for the total area of CKB. The trend of snow cover anomaly from its mean shows decrease in SCA over 18 years in winters except in December where the anomaly of SCA for the month shows stability in areal extent of snow cover (Fig. VI.5b). Monthly variation also shows decline in snow cover in January, February, March and increase in snow cover in ablation period (summer). Due to large uncertainty in the data these trends are statistically not much significant but decrease of SCA in the month of November partially supports this trend as the SCA mostly starts increasing from end of October till the month of March.

Seasonal snow cover trend although shows a considerable variability for both the accumulation and ablation periods, a significantly decreasing trend has been observed in all the winter months suggesting the decrease in the accumulation period snow pattern between 2002 and 2019, except in the month of December where statistically stable trend was observed (0.99 ± 2.01 %).

VI.2.4 Altitudinal distribution of SCA in CKB

Snow cover is critical for a wide range of hydrological studies, water supply and management applications. The present basin is widely distributed from 1540 m to 7000 meters a.s.l. The area between the altitude of 1540 m and 2500 meters a.s.l. has been referred as snow free zone in the present study. Snowfall generally doesn't occur even in winters at this altitude in the basin; hence, this area has not been taken into consideration for the study of SCA. The snow depletion curve based on altitudinal division shows maximum snow cover area takes place between altitude of 5000-5500 m a.s.l, which accounted for 24.76 % between 2002 and 2019, whereas minimum is at 6500-7000 meters altitude zone and contains only 0.28 % of the total basin area. This altitudinal zone (6500-7000 m a.s.l) is also considered as frozen zone and constant throughout the year as it contains accumulation area of all the glaciers in the basin (Fig. VI.6).

The SCA between the altitude 2500 m and 4500 m shows higher fluctuation in mean monthly snow cover area as it also includes seasonal snow cover. The month of March to October is taken null based on monthly snow line altitude (SLA) difference (Table VI.3). The SLA from January to December suggests that from 2500 m to 5500 m, there is fluctuation in SCA because of variation in seasonal snow in different months. Above 5500 m, due to being frozen zones, there is not much change in area of snow cover; it has 98-100 % snow cover all around the year. Table VI. 4 shows altitudinal variation in monthly snow cover in the basin and altitude based percentage of snow cover area.

Fig. VI.5: (a) Seasonal snow cover pattern in ablation period and accumulation period of 18 year where winter SCA is three times higher than summer SCA. **(b)** Anomaly in areal extent of SC from its mean for the month of December (Fall in winter snow cover on average especially in the month of Nov, Jan, Feb and Mar).

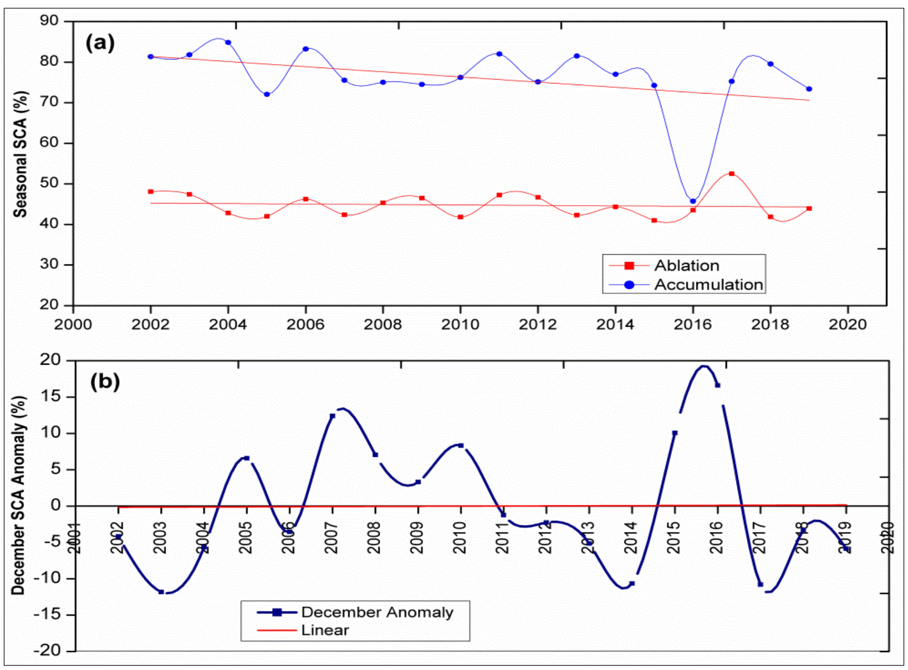


Table VI.3: Snow line altitude (m a.s.l.) estimate for the mean monthly snow cover

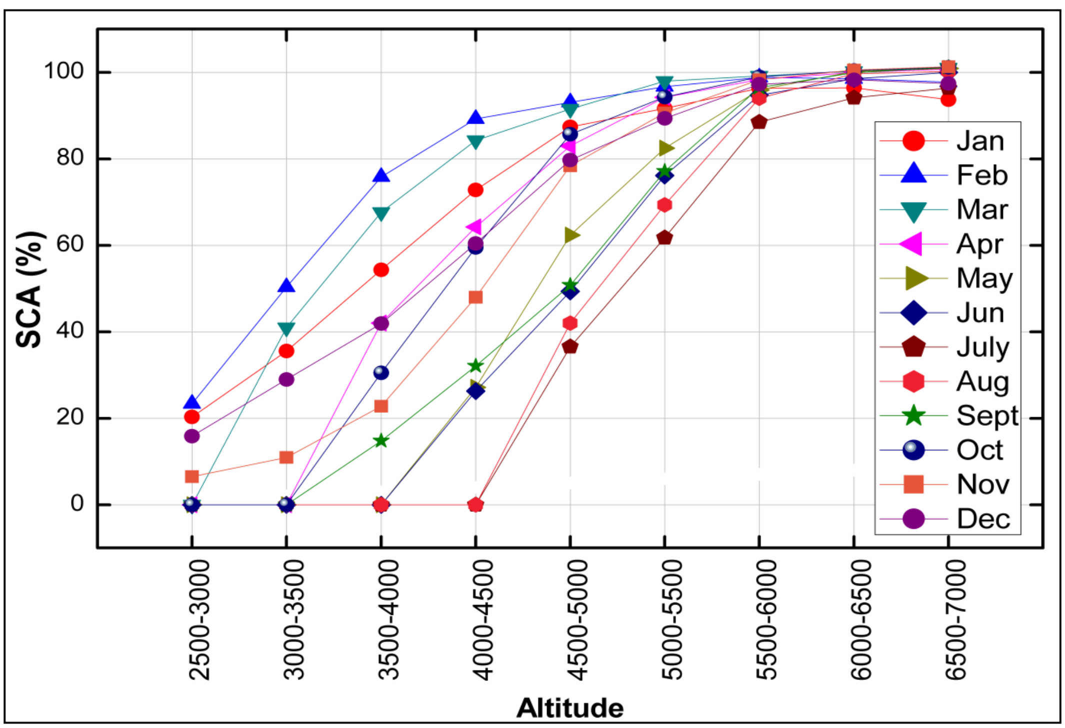
Period of Observation	Snow Line Altitude (m)	Period of Observation	Snow Line Altitude (m)
January	2950	July	5000
February	2800	August	4950

March	3000	September	4700
April	3950	October	4600
May	4400	November	4400
June	4800	December	3600

Table VI.4: Variation in percentage of snow cover area based on altitudinal division

	2500-3000	3000-3500	3500-4000	4000-4500	4500-5000	5000-5500	5500-6000	6000-6500	6500-7000
Jan.	22.30	39.96	60.47	78.46	90.45	93.77	96.20	94.94	86.60
Feb.	23.27	51.48	80.88	94.61	97.77	99.58	99.15	98.03	91.65
Mar.	-	45.62	71.37	87.50	93.66	98.18	98.29	98.48	94.79
April	-	-	42.85	64.36	84.18	95.04	98.11	98.53	96.85
May	-	-	-	28.45	64.59	83.93	96.53	99.21	97.65
June	-	-	-	27.59	49.85	77.04	95.09	98.11	97.01
July	-	-	-	-	38.18	64.16	90.35	94.29	94.75
Aug.	-	-	-	-	40.64	70.13	94.97	98.90	96.60
Sept.	-	-	15.23	32.46	49.37	76.54	96.30	98.58	97.26
Oct.	-	-	28.11	58.39	85.66	93.81	98.85	99.32	97.80
Nov.	6.61	11.28	21.07	46.51	77.33	89.67	97.99	99.10	97.66
Dec.	15.26	26.78	39.11	58.08	78.48	88.95	97.14	97.06	94.00

Fig. VI.6: Altitude-wise snow depletion curve- 2000-2019

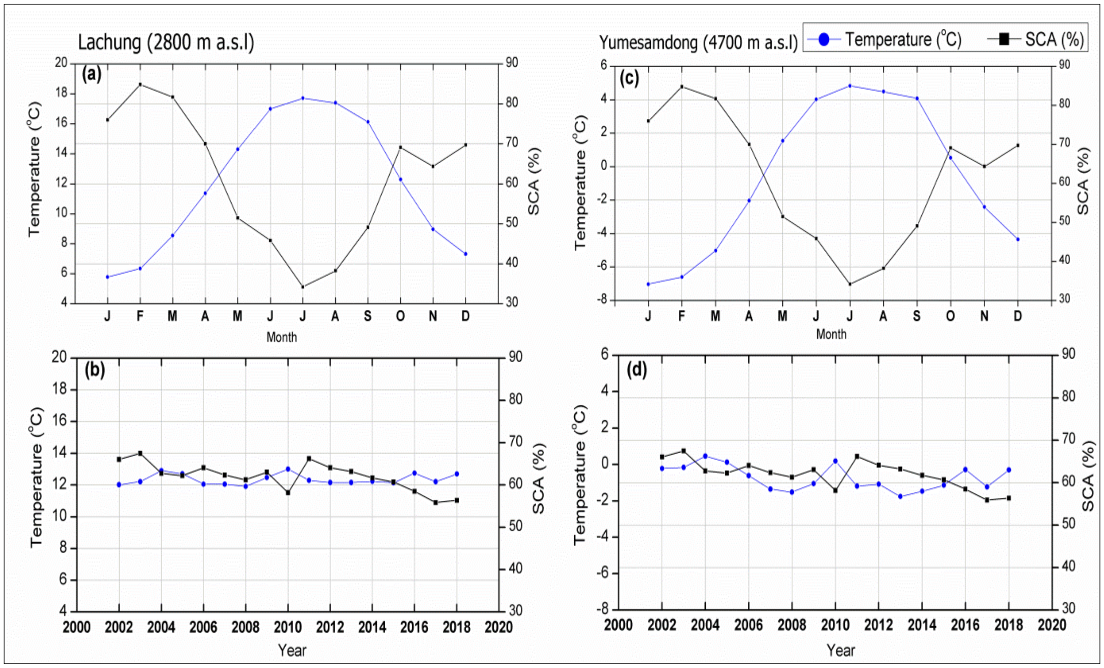


VI.3 Relationship between SCA and Temperature

To understand the relationship between annual mean SCA and climatic parameters from 2002 to 2019, the SCA is correlated with temperature data. Analysis of the monthly mean SCA and temperature between 2002 and 2018 shows a negative correlation between the two, that is, increase in temperature leads to decrease in areal extent of snow cover in the same month (Fig. VI.7a, c). Dividing a balance year into two season (i.e. accumulation and ablation) a gradual increase in temperature in the basin were found at the start of march and simultaneously the decrease in SCA. The SCA reached to minimum in July (35%) when temperature reaches to its maximum of 18 °C and 5 °C at Lachung and Yumesamdong, respectively. The distribution of mean monthly snow depletion curve shows that as the temperature increases, the mean monthly areal extent of snow cover in the basin decreases (Fig. VI.7a, c). The maximum temperature observed in the month of July, it fits well with the minimum extent of snow cover in the same month.

For most of the year, the temperature is zero degree or below in Yumesamdong (4800 m a.s.l) and which also supports the analysis that highest SCA was observed in the altitude 6000-6500 m. The temperature trend has been consistent in Lachung (2800 m a.s.l) over 17 years whereas its shows a decreasing trend in higher altitudes of the basin (4800 m a.s.l) (Fig. VI.7b, d). The higher altitudes of the basin shows much fluctuation in temperature as compared to the lower reaches, however the trend is more or less increasing at both the altitudes with varying rate.

Fig. VI.7: Relationship between SCA (%) and temperature (°C), **(a, b)** mean monthly and annual relationship at the Lachung (2800 m a.s.l) and **(c-d)** at the Yumesamdong (4700 m a.s.l) for the period of 2002-2018.



Snow is an essential component of the Cryosphere and glaciers that helps to regulate the temperature of the Earth's surface along with providing water to the perennial rivers (Bolch and Christiansen 2015; Hock et al., 2017). The atmospheric changes may lead to reduction in snowfield and amount, and can cause great influence on the temperature and precipitation regime of any area which differs from one location to other. Previous studies on snow assessments also suggests that snow cover has decreased in last three decades over the Himalayan region (Gurung et al., 2011; Gaddam et al., 2018; Krishna et al., 2011; Zhang et al., 2020).

Decadal snow cover assessment in Sikkim including CKB showed decline of SCA by 2.81 ± 2.02 % (Basnett and Kulkarni 2019). Monthly snow cover observations showed that Sikkim received the maximum snow in February (~50 %) and present study in Changme Khangpu basin shows the maximum extent in February and March (~85 %)

only, similar to basin of Bhutan (Gurung et al. 2011). However, the highest snow cover area was observed in the month of January in the Kashmir valley and the Tibet regions (Dahe et al., 2006; Negi et al., 2009) and in March in the Baspa basin in western Indian Himalaya, and in west China (Dahe et al., 2006; Kaur et al., 2009). The western Himalaya receives more precipitation from Western Disturbances as compared to the central part (Bookhagen and Burbank 2010; Kumar et al., 2014; Dimri et al., 2015; Krishnan et al. 2018). In the western Himalaya, the SCA shows declining trend from March onwards, same as compared with the eastern Himalaya (Kulkarni et al., 2010). Although the eastern and the central Himalaya have received a decreased extent of SCA in last three decades, but a current study in the Upper Indus basin (UIB) by Bilal et al. (2019) suggests that annual SCA has increased over the period between 2000-2017. Few other studies in the UIB reported similar result of increasing SCA over the last decade (Hayat et al., 2019; Yaseen et al., 2020). These east-west SCA variations observed over the Himalaya may attribute to the upper air circulation and weather systems, which influence the timing of maximum snowfall occurrences across the Himalaya. Further, the SCA assessment also suggests that the melting of snow and glaciers starts from the end of March, it continuously contributes to the stream runoff in the Lachung River until August in CKB. Changes in climate or regional weather pattern (temperature and precipitation) also influence the timing of winter snow as well as the amount of snowfall.

The snow cover between 2002 and 2019 showed fluctuations in peaks in the month of February and March (maximum) as well as June and July (minimum). The maximum extent of snow cover area was in February 2003 ~92.8 % of the total basin area (737.36 km^2) and minimum in November 2017 around 34.95 % (276.81 km^2). The influence of

Western Disturbances in the basin exists which contributes higher in the month of February-March. There is continuous snow precipitation from January till the end of April in the higher altitudes of the basin. Whereas in the Western Himalaya the SCA shows declining trend from March onwards (Kulkarni 2010). It also indicates the pattern of snow accumulation and ablation is different in the eastern and the western Himalaya. From the month of April onwards, SCA starts decreasing with the lowest in the month of June 46.71 ± 5.24 %, July 34.17 ± 5.83 % and August 38.23 ± 6.52 %. The mean annual SCA was highest in 2003 (67.46 ± 10 %) and lowest in 2017 (54.21 ± 9.1 %). Decrease in winter seasonal snow (January, February and March) in the year 2017 resulted in lowest mean SCA in this particular year. Higher fluctuations in snow cover were observed in the accumulation period because of the frequent snowfall and melting at lower altitudes. The study also shows that snow cover area in accumulation period is decreasing while it is showing increasing trend in ablation period. The maximum temperature is observed in the month of July which fits well with the minimum extent of snow cover in the same month. The monthly trend of SCA starts decreasing from April onwards with the increase in temperature of the region and contributes continuously to snowmelt runoff in the basin till August. Both, high temperature and precipitation of July leads to lowest SCA in the same month due to continuous melt at lower altitudes and accumulation in higher region of the glacierized basin at the same time. These variations in the snow covered peaks observed over the Himalaya (Western, Central and Eastern Himalaya) could be attributed to the upper air circulation and weather systems. These variations influence the timing of maximum snow fall occurrences across the different parts of Himalaya.

Chapter VII

Glacier Mass Balance

The Indian Himalaya in the Hindu Kush Himalayan region consisting of 9,575 glaciers with an area of ~40,000 km^2 and an ice volume of ~2,000 km^3 (Raina and Srivastava, 2008). Recent discussions on the rapid shrinkage of Himalayan glaciers than other parts of the alpine glaciers have emphasized the need of more knowledge about the glaciers health in this region (Cogley et al., 2010). Therefore, glacier mass balance assessment is crucial as it is a key indicator of glacier health and regional-scale climate change. Mass balance can be measured through the glaciological, hydrological, AAR/ELA and geodetic methods (Pratap et al., 2016). Himalayan glaciers being located in remote and arduous terrain, monitoring of glaciological mass balance requires lot of logistic efforts to study (Raina, 2005, 2008, 2009). Thus, only 20-25 glacier's in-situ mass balance measurements have been made on Himalayan glaciers (Azam et al., 2018). The hydrological method relies on the estimates of annual accumulation, ablation from snow-meteorological and discharge data. However, owing to unavailability of such data only one glacier (Siachen) have been studied using hydrological mass balance (Bhutiyani et al., 1999). Geodetic method is based on the assumption that a change in elevation over time from digital elevation model (DEM) constructed over the glacier region from topographic maps, satellite or digital aerial photographs can be translated into a change in mass (Bamber and Rivera, 2007; Bhambri and Bolch, 2009). Thus, there is an urgent need to develop and adopt an alternative indirect method for realistic mass balance estimations. Conceivably the main attractive indirect assessment of mass balance is to use the in-situ equilibrium-line altitude (ELA) or accumulation-area ratio (AAR) and specific balance statistical relationship (Ostrem, 1975; Braithwaite and Muller, 1980; Braithwaite, 1984; Kulkarni, 1992). Changes in AAR directly speculate fluctuation in ELA and specific mass balance

(Braithwaite, 2008). Some studies have demonstrated that if the relationship between AAR or ELA and specific balance is established, specific mass balance can be computed from the ELA or AAR using remote sensing method (Ostrem, 1975; Braithwaite, 1984; Kulkarni et al., 2004; Rabatel et al., 2005; Brahmbhatt et al., 2011; Pelto and Brown, 2012).

Studies also suggests that a number of glacier morphological aspects such as glacier shape and size, hypsometry, and bed topography canbe investigated using remote sensing based techniques, and these parameters can be used for understanding the glacier mass balance. Therefore, to overcome the complexities of mass balance estimation using glaciological, hydrological and geodetic methods, Kulkarni, (1992) proposed AAR and specific mass balance relationship for Baspa basin in Indian Himalaya. Over all, there are two possibilities for mass balance estimation: (1) develop statistical relationship between in-situ ELA or AAR and mass-balance series and estimate mass balance for additional unknown years using AAR or ELA data derived from remote sensing; and (2) calculate mass balance for glaciers using regional generalized statistical relationship of ELA or AAR and specific balance series where no in-situ mass balance measurements have been made. On regional scale ELA for the Himalayan glaciers may be one single value but it has been observed to vary for individual glaciers due to topographic variations, and microclimatic parameters prevailing in the valley. Under such circumstances the ELA across the width of the glacier may also vary with altitude. Also, ELA estimation corresponds to linear approach and separates the accumulation and ablation zone of glacier. AAR could be a more reliable and better proxy to estimate mass balance by AAR and specific balance statistical relationship as AAR is the ratio of accumulation area to total glacier area.

Later approach was used by Kulkarni et al., (2004) for estimating the mass balance of 19 glaciers in the Baspa basin, Himachal Pradesh. Recently glacier mass balance estimation was carried out for the Indian Himalayan glaciers of ten basins using Kulkarni et al., (2004) AAR and specific balance model (MOEF and SAC report, 2011). However, strength of this regression model is still to be ascertained for Himalayan glaciers which nurture different climatic and topographic regime. One of the recent studies by Pratap et al. (2016), presents the mass balance estimation of Himalayan glaciers using different methods (Glaciological, Hydrological, Geodetic and AAR/ELA) and compared the in-situ specific mass balance with AAR derived specific mass balance from 11 Indian Himalayan glaciers and proposed a second regression model for diverse climate regimes of Himalaya.

Therefore, this work is intended to calculate specific mass balance based on both the developed regression equations for the Himalayan glaciers, as eastern Himalaya lacks in-situ study of mass balance except in the years 1980 to 1986 by Nijampurkar et al., 1985 and Raina and Srivastava, 2008. However, the present study could not compare the existing in-situ data with the present remote sensing derived specific mass balance due to lack of data sets and availability of imageries from the past. In this study, remote sensing derived Equilibrium Line Altitude (ELA) and Accumulation Area Ratio (AAR) for Changme Khangpu Glacier between 2008 and 2019 were used to estimated specific mass balance with the help of the modeled equations by Kulkarni et al., 2004 (Eq. i) and Pratap et al., 2016 (Eq. ii). Equation (i) is derived using the in-situ mass balance data series collected by GSI for two glaciers during 1976-1984 and 1982-1988 for Gor Garang Glacier and Shaune Garang Glacier, respectively.

VII.1 Study Site and Methods

The mass balance estimation was studied for Changme Khangpu Glacier in North Sikkim, eastern Himalaya, India (27° 53' 43'' N, 88° 41' 17'' E). The Glacier lies in Changme Khangpu basin and is 5.65 km long and covers an area of~ 4.85 km^2. The elevation of the glacier ranges from 4850 to 5650 m a.s.l with a slope of <10°. The ablation area of the glacier is heavily debris-covered ~80-90% of the total area (Raina & Srivastava 2008; Pratap et al. 2016). The glacier has many seasonal supra-glacial lakes those changes with time and space. The orientation of this glacier is north-south facing. The balance year for this glacier is from 1stNovember to 31stMarch for accumulation season and from 1stMay-31st October for ablation season. This region is influenced by western disturbances and Indian Summer Monsoon (ISM), which contributes a significant amount at the upper reaches of glaciers in the basin and the Glacier falls under the summer accumulation type glacier. The region shows maximum melting during the month of July- September, which is considered as right time to study the changes in characteristics of glacier mainly- shape, length, mass and volume of glacier.

The present study was carried out using remote sensing based ELA/AAR modeled estimation of mass balance. The ELA was derived from different sets of imageries namely- LISS-III, AWiFS, Landsat TM, Landsat ETM+, Landsat OLI, Sentinel-2A, between 2008 and 2019.The satellite imageries selected for demarcation of ELA of the Changme Khangpu Glacier is mainly from the month of September and October, when the region has least snow cover in the basin. The details of images are presented in Table 1.

In order to distinguish glaciers zones (i.e. accumulation and ablation zone), the NDSI and band ratio techniques were used. The pre-processing of satellite imageries includes sensor calibration, radiometric calibration and conversion of DN to Radiance. Then with the help of NDSI and band ratio techniques, the snow and ice from other parts of the glacier with the help of SWIR and green bands were distinguished. The glacier extent was marked with semi-automatic method as well as manual delineation using Sentinel-2A MSIL1C imageries. A standard threshold of 0.4 was applied for the process of further delineation of the two zones. After applying threshold, accumulation area is estimated which results in the evaluation of accumulation area ratio (AAR) with the help of ELA demarcation and finally the mass balance.

Table VII.1: Satellite details used for the demarcation of Equilibrium Line of Changme Khangpu Glacier

Sl. No.	Satellite Image Type	Acquisition Date
1.	LISS- III	17th September, 2008
2.	Landsat-7 ETM+ and Google Earth	30th October, 2009
3.	Landsat-7 ETM+	30th October, 2010
4.	Landsat-7 ETM+	27th September, 2011
5.	AWiFS	30th October, 2012
6.	Google Earth imagery	23rd October, 2013
7.	Landsat-8 OLI	6th October, 2014
8.	Landsat-8 OLI	7th September, 2015
9.	Sentinel-2A MSIL1	27th October, 2016
10.	Sentinel-2A MSIL1	17th October, 2017
11.	Sentinel-2A MSIL1	17th September, 2018
12.	Sentinel-2A MSIL1	22nd October, 2019

Using the set of multiple images from all the secondary sources, first the ELA of Changme Khangpu Glacier have been marked (Table 1). The equilibrium line of a glacier is where the accumulation equals the ablation over a one-year period. After identification of ELA for every single year between 2008 and 2019 (Fig. 1, Table 2), the AAR for the glacier was estimated using the derivation as:

AAR = Accumulation area ⁄ Total glacier area.

Table VII.2: ELA and AAR estimated during 2008-2019 for Changme Khangpu Glacier.

Year	AAR	ELA	Year	AAR	ELA
2008	0.51	5320	**2014**	0.48	5325
2009	0.47	5335	**2015**	0.60	5230
2010	0.52	5305	**2016**	0.48	5330
2011	0.52	5310	**2017**	0.53	5260
2012	0.52	5320	**2018**	0.51	5295
2013	0.51	5310	**2019**	0.51	5275

Fig. VII.1: Relationship between AAR and ELA of Changme Khangpu Glacier

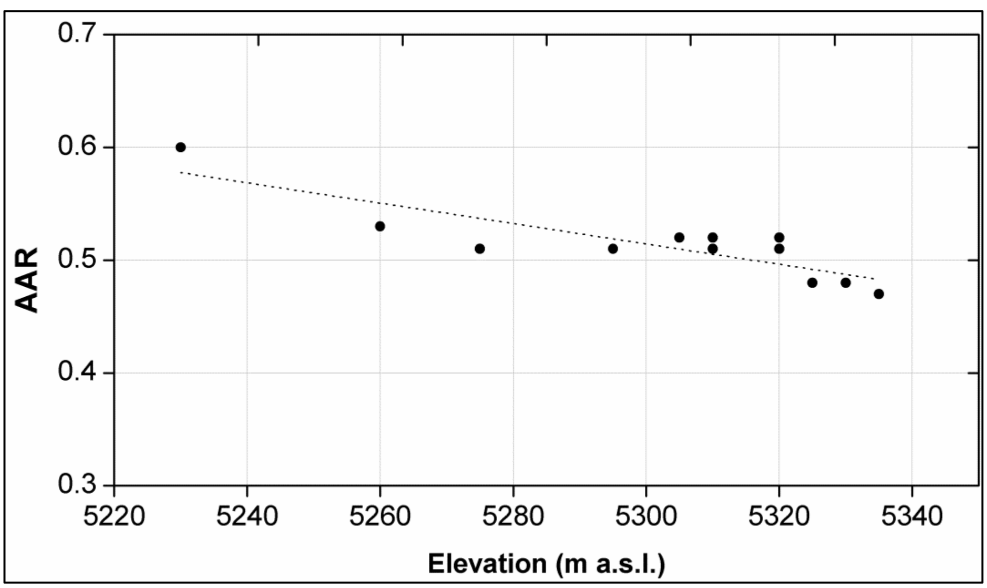
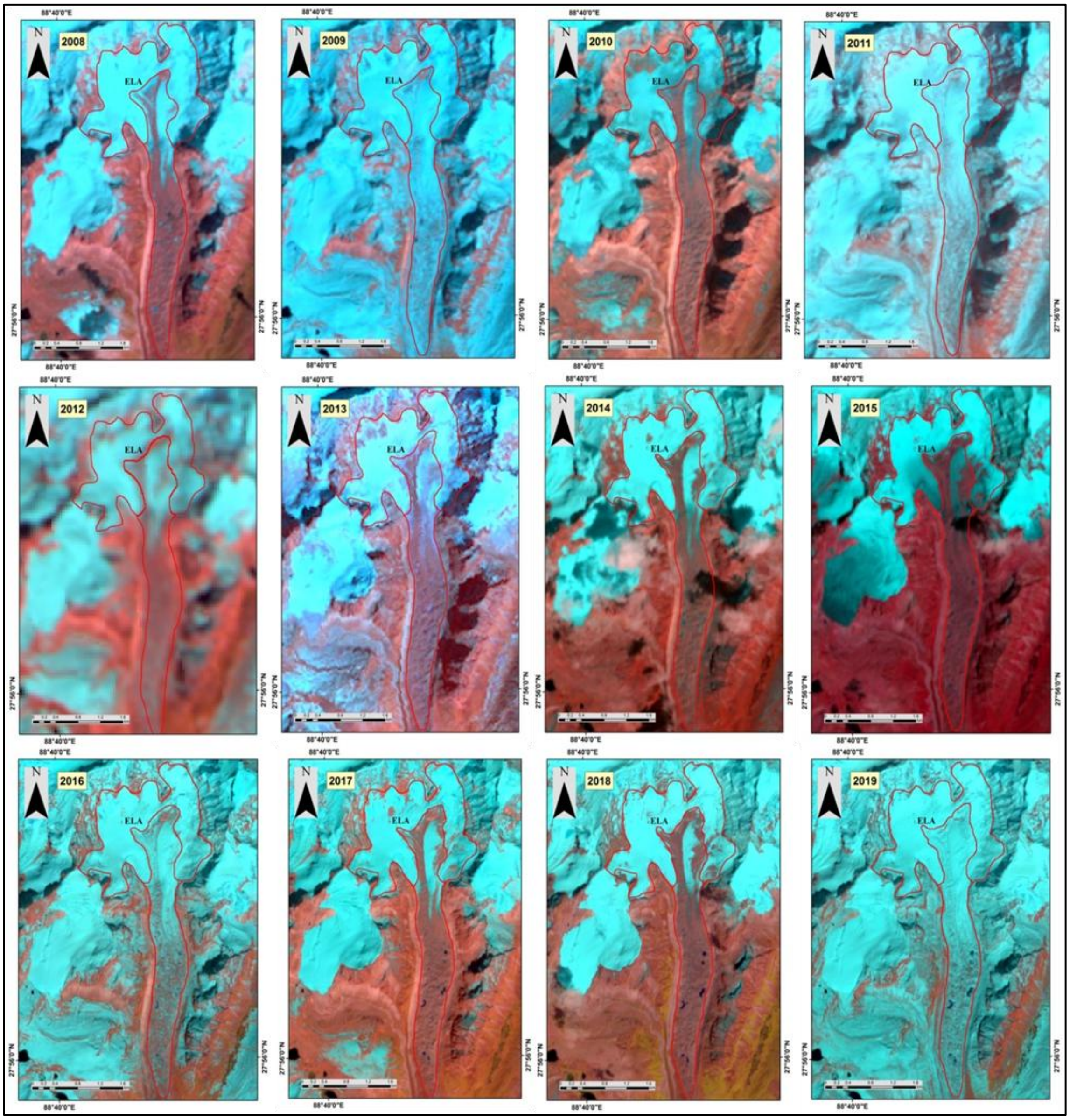


Fig.VII.2: Equilibrium line altitude (ELA) marked over Changme Khangpu Glacier from 2008 to 2019 and mean ELA was 5301 m a.s.l.



The following regression equation developed by Kulkarni et al., (2004) was used to scrutinize the specific mass balance values for the period of 2008-2019.

$Y = 2.4301 * X - 1.20187$ **(i)**

Where, Y is the specific mass balance in meter water equivalent (m w.e.) and X is the AAR.

In addition, the recent regression equation developed by Pratap et al., 2016 was also used in the present study, as both the regression equation's have been developed from different parts of Himalaya.

$$Y = 1.9433 * X - 1.3149 \qquad \textbf{(ii)}$$

In order to understand the suitability of the developed equation in this part of the Himalaya, both the equations have been used and also compared with existing in-situ specific balance observations (1980-1986) for Changme Khangpu Glacier.

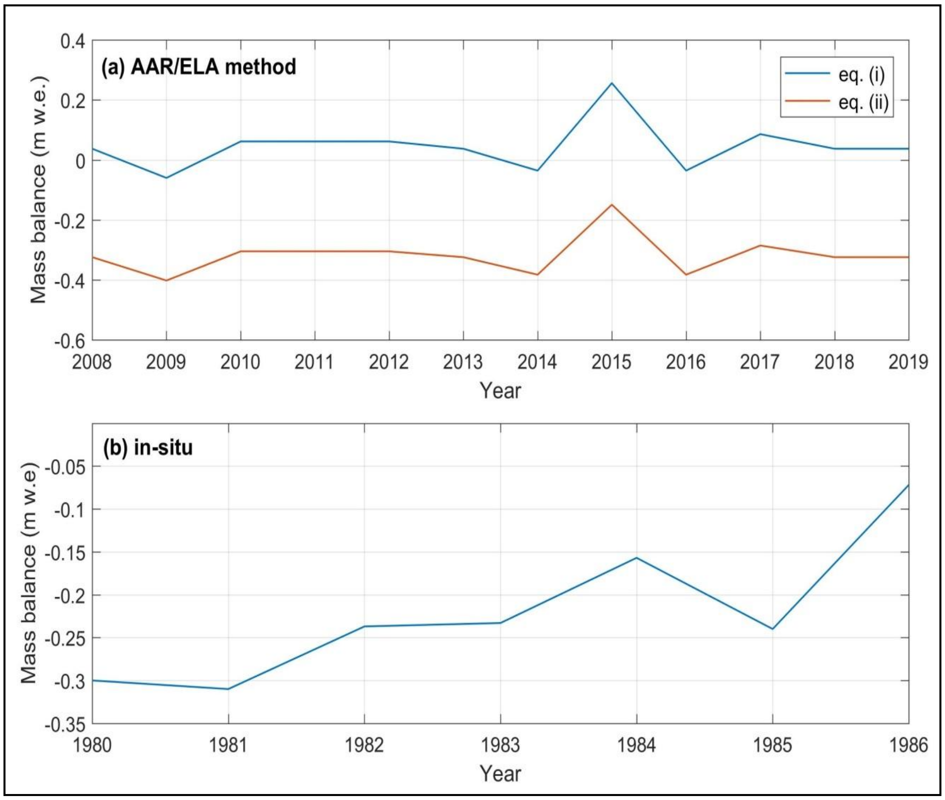
VII.2 ELA, AAR and Mass Balance

The statistical relationship between ELA and AAR is inverse. Changes in AAR directly effects the ELA fluctuation and specific balance of glacier. Decrease in ELA increases the ratio of accumulation area to its total area (AAR) and decrease in AAR leads to increasing glacier mass balance or high loss in glacier mass. Topographic characteristics such as type of glacier, number of tributary glaciers, shape/size of accumulation and ablation area, local climate regime, ice avalanche, small elevation range and debris cover over the glaciers are the major factors which can influence the relationship of AAR and specific balance for Himalayan glaciers.

The regression equation used for the estimation of specific mass balance based on both the studies (i.e. eq. i and ii) shows some uncertainty between the two results.

The results suggest that the specific mass balance derived using regression equation (i) is highly uncertain because of the fact that the model was developed using the in-situ data of western Himalayan glacier's only till the year 2004. On the other hand, comparatively good agreement using equation (ii) proposed by Pratap et al. (2016) has been observed as the second model was developed using the in-situ data of all the Himalayan glaciers till the year 2014 (Fig. VII.3a). The existing in-situ data of mass balance of Changme Khangpu Glacier (1980-1985) shows a similar trend as that of the present modeled data (Fig. VII.3b).

Fig. VII.3:(a) trend of modeled mass balance using both regression equations between 2008 and 2019 **(b)** trend of mass balance using in-situ data of Changme Khangpu Glacier during 1980-1986.



Source: (b) In-situ mass balance data is based on studies of Nijampurkar et al., 1985; Dyurgerov & Meier, 2005.

Kulkarni, (1992) estimated 0.44 for the AAR representing zero mass balance in the western Himalaya using two glaciers time-series data. In addition, one more study reported AAR_0 on the basis of three glaciers data series ranged from 0.43 to 0.58 (Mukherjee and Sangewar, 1996). Study by Pratap et al. (2016) found that individual balanced budget AAR (AAR_0) ranged from 0.14 for Dunagiri Glacier and 0.72 for

Dokriani Glacier. Similarly, ELA_0 ranged from 4809 m a.s.l for Dunagiri Glacier and 5163 m a.s.l for Gara Glacier. The combined regression analysis generated from entire time series-data of specific balance, AAR, and ELA for six Himalayan glaciers show 0.53 for AAR_0 and 5000 m asl for ELA_0. It is evident that generalized, AAR_0 for Himalaya depends on number of samples used for specific balance and AAR analysis. Increased number of mass balance (in-situ) data increases the reliability and efficiency of the regression equation.

However, for the present study, the ELA ranged from 5230 m a.s.l (minimum) in 2015 to 5335 m a.s.l (maximum) in 2009 for Changme Khangpu Glacier between 12 years. The AAR for the same Glacier ranged between 0.47 to 0.60, much higher as compared to the glaciers of western and central Himalaya. Similarly, the highest ELA mark is observed for Changme Khangpu Glacier itself (5230 m a.s.l to 5335 m a.s.l) as compared to the other glacier in Indian Himalaya like- the higher ELA data series represents the Chhota Shigri (4855 to 5185 m a.s.l), Gara (5050 to 5300 m a.s.l), Gor-Garang (4980 to 5230 m a.s.l) and Dokriani (5030 to 5110 m a.s.l) glaciers. All these glaciers have similarities in orientation except for Gor-Garang. The lower ELA data series concerns with small elevation range and avalanches feeder zone in the accumulation area such as for Dunagiri (4835 to 4870 m a.s.l) and Shaune Garang (4770 to 4970 m a.s.l) glaciers. The orientation of Changme Khangpu Glacier is also different from rest of the glacier's mentioned as Changme Glacier is south facing similar to Gor-Garang in Baspa basin, western Himalaya and melting of snow/ice is higher as compared to the north and west facing glaciers.

As the Changme Khangpu Glacier is highly debris-covered and avalanche fed, the fluctuation in ELA is found less in recent period and is maintained at particular altitude. The present study also suggests that since the ELA of this glacier is already at the higher position and it can be altered by avalanche as well, the melting of this debris covered Glacier may reduce in the coming years or near future.

Optical data because of their high resolution is useful to distinguish between accumulation and ablation zones of glacier by applying appropriate threshold value on NDSI and Band Ratio. This further helps in delineation of ELA on the glacier area for every single year to minimize the visual interpretation which can occur during direct demarcation of ELA. The studies in different parts of Himalayan region (western-central and Karakoram region) shows that the mass balance estimation done using AAR technique by remotely sensed data can directly estimate the total loss and gain in glacier. These studies have been also validated in the field with the help of field mass balance and AAR estimation. The present studies also report that Changme Khangpu Glacier has experienced loss in its glacial mass over the period of 12 years, however the ELA of this glacier does not show much fluctuation. The specific mass balance (SMB) value is estimated for Changme Khangpu Glacier to be:

Table VII.3: Modeled specific mass balance (SMB) estimated using AAR derived from remote sensing.

Year	Accumulation Area (km^2)	AAR	Mass Balance (Eq. i)	Mass Balance (Eq. ii)
2008	2.32	0.51	0.04	-0.32
2009	2.36	0.47	-0.06	-0.40
2010	2.53	0.52	0.06	-0.30
2011	2.48	0.52	0.06	-0.30
2012	2.43	0.52	0.06	-0.30
2013	2.48	0.51	0.04	-0.32
2014	2.51	0.48	-0.04	-0.38

2015	2.44	0.6	0.26	-0.15
2016	2.46	0.48	-0.04	-0.38
2017	2.50	0.53	0.09	-0.28
2018	2.47	0.51	0.04	-0.32
2019	2.42	0.51	0.04	-0.32

VII.3 Limitations of AAR Method

The remote areas of mountainous region, its rugged topography and unpredictable weather is always a limitation for the field-based study and which can be fulfilled with the help of remote sensing based observations. AAR method provides a better platform for the study of mass balance but with certain limitations. If the field-based mass balance and AAR data is available for certain years, then the mass balance for subsequent years of the same glacier with the help of AAR derived from remote sensing method can be done easily and continuous monitoring is possible. But the lack of field data is a major hindrance in this part and the reliability of this technique mainly depends on the availability of data. Remote sensing based study needs further parameters like- ELA (elevation), AAR and glacier density and thickness to estimate mass balance. The optical data in the mountainous regions suffers mainly from high cloud cover and shadows, with the snow-covered topography which makes its use limited. Since the present study needed data from a particular time period of the year (September or month of October), the availability of satellite data will be useful only which frequently passes through this region at that period of year and should be cloud free to differentiate between snow and ice.

<u>Summary and Conclusion</u>

The Himalaya covers around 10% of ice (glaciers and ice niches), and Cryosphere area could be as much as 20% more than solid glacier cover. Role of the Cryosphere in controlling temperature through albedo effect is also an important aspect to understand glacier formation, melt water discharge and glacier–climate interaction. Consequences of the loss of Himalayan cryosphere on society invite immediate attention and necessary evaluation of all these environmental parameters, so that a resilient and robust future plan could be drawn. In conjunction with glacier shrinkage, many of these systems will suffer from altered precipitation regimes, drought, and reduced snowpack, further exacerbating effects of climate change on water supply (Barnett et al., 2005, Stewart, 2009). Moreover, mountain glaciers are one of the sensitive probes of local climate; thus, they present an opportunity and a challenge to interpret climates of the past and to predict future changes (Owen et. al., 2008, 2009). Besides, glaciers can constitute hazards, including GLOF's, changes in magnitude and timing of runoff and through worldwide loss of glacier ice-a global rise in the sea-level change (Kaab et al., 2005).

Large variability in topographic extent with different climatic zone over the Himalayan arc makes Himalayan glaciers respond heterogeneously in terms of mass balance, retreat rate and other response to climatic variations. In order to understand behavior of glacier and variation in seasonal snow cover in the area, this study was carried out in northern most part of Sikkim’s Changme Khangpu Basin. The study also highlights the influence of local weather pattern and precipitation regime on glacier behavior and altitudinal change in snow covered area, which ultimately contributes to meltwater runoff in the rivers.

I.1. Mountain glaciers being an integral part of the Cryosphere constitute one of the vital components of Earth’s natural systems and are prime reserves of fresh-water.

High sensitivity of glaciers to changes in the elements of climate render them excellent indicators of prevailing climatic changes.

I.1a. In view of the vastness and inaccessible nature of mountain glaciers, remote sensing is perhaps the only effective tool for their comprehensive and cyclic data acquisition in a cost-effective manner. However, detailed glaciers' ice mass variation data are still lacking for most parts of the world.

I.1b. The Himalaya- also referred to as the 'Third Pole' and Water-Towers of Asia supports billions of lives downstream; thus, climate remains the major driving force for almost entire Asia. Anthropogenic changes have led to more demand for water as well as other environmental resources in the modern industrial world.

I.1c. The impacts of glacier shrinkage on social, economic and ecological systems are multi-faceted. The surge of glacial meltwater into rivers will be transient in terms of difference in melting and total contribution to the river system. However, in conjunction with glacier shrinkage, many of these systems will suffer from altered precipitation regimes, drought, and reduced snowpack; thereby exacerbating the effects of climate change on water supply

I.2. Limited studies have been conducted on the northern most part of the Sikkim especially on snow melt contributing to river discharge in the area and associated rate of erosion by water flow. The foregoing gap prompted to take this study and generate field-based data for this part of the Himalaya.

I.3. Present study has been carried out in the Changme Khangpu basin which covers an area of 792 km^2 in the North district of Sikkim. It includes many debris covered glaciers, hanging glaciers, clean glacier and rock glaciers. It has many tributaries to the main river *Lachung Chhu* in the valley; the *Lachung Chhu*, in turn surrenders itself to river Teesta.

I.4. In order to understand the ongoing climatic variation and associated changes in the Himalayan glaciers, the study focused on monitoring of glaciers, snow cover changes, meltwater discharge and sediment supply. Glacier monitoring was done for a longer period between 1962 and 2018 for Changme Khangpu and for other glaciers it was studied between 2005 and 2018. In order to understand the behavior of Changme Khangpu Glacier, the mass balance study was also conducted based on ELA fluctuation.

I.5. These studies were done using various satellite imageries like Landsat, Sentinel-2A, LISS-III, AWiFS, MODIS and DEM and using remote sensing techniques and GIS applications. The imageries were analyzed with multiple semi-automatic methods and manual observation. Field study was undertaken also to understand landforms, water discharge and sediment-flow during 2016 to 2018.

II.1. Mountain cryosphere systems are among the key areas to understand the effects of the global climate change. Any variation in it can influence the hydrological cycle and in turn can increase related natural hazards. Therefore, it needs higher attention.

II.1a. Regional climate models predict that the change in certain climate elements such as air temperature, moisture source and albedo, will be accelerated within mountain systems as compared to predicted global means.

II.2. Previous Studies from around the world analyzed the mean specific mass balance of the Indian Himalaya and other mountain glaciers (e.g. Andes, Alps) and found that most of the mass balance series are negative.

II.3. The Hindukush Himalaya alone carries more than 54, 000 glaciers with and area of 60, 000 km^2, where the Indian Himalayan region only reports more than 10,000 glaciers and most of them are debris covered (Raina and Srivastava, 2008; Shukla et al., 2018; Pratap et al., 2016).

II.3a. It has also been assumed that the glaciers in the Himalaya and the Trans-Himalaya are influenced by changes in the influx of moisture and heat and by inter-annual variations in the character of the monsoon.

II.4. Remote Sensing and GIS based monitoring of glaciers has gained utmost importance with time owing to large aerial coverage with lesser human accessibility because of the rugged terrain and unpredictable weather patterns in the Himalayan regions.

II.4a. Glacial-discharge contributions in the higher altitudinal areas are more complex. Limited mass–balance studies and studies measuring the seasonal waxing and waning of glaciers suggest a significant glacial contribution to discharge.

II.4b. Snowmelt was found to be the most important water source during pre-monsoon season whereas rainfall and glacial melt are key contributors to river discharge during summers.

II.5. More than 50% of the annual discharge comes from snowfalls associated with the westerlies in the Northwest and the Eastern Himalayas. Whereas, the Central Himalayan rivers generally receive less than 25% of their annual discharge from snowmelt, and are instead fed mainly by summer monsoon rainfall.

III.1. The topographical control over the Changme Khangpu basin shows that about 90 % of the basin area lies above 3000 meter above sea level (m a.s.l) with slopes above 45^{o}, except in the valley bottoms.

III.1a. The study area receives an annual rainfall of 2401 mm and also receives precipitation in the form of snowfall above 2800 m a.s.l.

III.1b. Temperature varies from 9-25 ^{o}C in summer and -7 to 9 ^{o}C in winters. Climate zone between the altitude of 4500-5500 m is polar tundra type characterized by cool summer, cold winter and a summer rainfall regime and contains most of the glaciers.

III.2. The geology of Changme Khangpu basin lies in the Higher Himalayan crystalline, which is bounded by the Main Central Thrust in the South and the South Tibetan Detachment System in the North.

III.3. In total, 58 glaciers were identified which varies between 0.28-22.54 km^2. The basin is characterized into five elevation zone with the main focus on glaciated area.

III.3a. The Basin has widespread debris-covered ablation zone, and signifies that the area is under higher melting condition. The total area under clean glacier is around 50.19 km^2 which is around 71 % of the total glacier area and higher than debris covered glacier which accounts for 28.99 %.

III.3b. In general, the glaciers in the Himalaya are lies above 3500 m a.s.l (Kulkarni et al., 2007; Gaddam et al., 2018; Shukla et al., 2018) while in the Changme Khangpu basin, glaciers elevation ranges between 4500 to 7000 meters.

III.3c. The geomorphic processes like concentrations of rockfalls and debris are generally prevalent in the extreme north and south of the basin.

III.3d. Moraines are concentrated at an elevation of 3000 meters or above and are large as well as kilometres long. Apparent Increasing length of lateral moraines has also been observed indicating the reduced glacierized area in the basin.

III.3e. Glacial lakes are only encountered within frigid zone and which is also the main source of fresh water for the people downstream.

III.3f. Changme basin has dominant active glacial processes in the northern parts; while the presence of braided channels, gullies, river terraces, bar deposits, etc. shows the fluvial processes are dominant in the other half of the study area.

III.3g. Numbers of glacial lakes have been increased over period of time indicating receding glaciers in the area. These lakes are formed along edges of moraines and moraine dampening or heavy rainfall might cause glacial lake outburst phenomena in the coming years.

IV.1.1. 70 to 80 % of the Himalayan glaciers are either thick debris-covered or with thin debris on the lower part; it continues to pile up since the little ice age.

IV.1.1a. Glacial sediments are transported from accumulation zone to the snout forming moraines, corrie or cirque etc. Various glacial features e.g. lateral, medial and terminal moraines, pro-glacial lakes preserve information about climate, erosion rate, deposition and tectonic evolution of the area.

IV.1.1b. Sediments characteristic in the glacial environment is a function of lithology and geochemical properties of the sediment source, nature, distance of sediment transport, and the mode of sediment deposition.

IV.1.2. Changme Khangpu Glacier is 5.65 km long and covers a total area of ~4.85 km^2. Ablation area of the glacier is heavily debris-covered ~80-90% of the total area (Pratap et al., 2016).

IV.1.3. Field study from proglacial to the accumulation zone of the Changme Khangpu glacier catchment area has been conducted to identify different types of geomorphic landforms and features.

IV.1.3a. The geomorphic features identified were Glacio-fluvial Sediment, Snout, Lateral Moraines and Accumulation zone. Total thirteen sediment samples were collected from four different sites highlighting source areas.

IV.1.4. The textural studies based on grain size analysis shows coarser as well as fine size fractions in variable proportion. The sorting of the sediments varies widely between poorly sorted to moderately sorted indicating glacial and glacio-fluvial processes were operational over the area.

IV.1.4a. The skewness differs from symmetrical, coarse skewed and fine skewed infers mixed size fractions of sediments. In the upstream, sediments are fine skewed and in the downstream sediments are coarse skewed which supports that the sediments are coarser upstream and get finer after it has travelled a distance.

IV.1.4b. The change in modality of samples from unimodal, bimodal and trimodal confirms fluctuation in energy conditions of transporting agent. Grain size decreases with the stream distance and coarse sediments away from the source site indicates that the velocity of the stream was very fast.

IV.1.4c. Present study concludes that depositional landforms of accumulation zone and lateral moraines are developed through comparatively more dynamic glacial processes while snouts and glacio-fluvial regions are developed in response to fluvial processes.

IV.1.5. The mineralogical studies of finer fractions of sediments indicate identical mineral assemblage of source rock because of the presence of quartzo-feldspathic, mica and alumino-silicate minerals in the sediments. It indicates that they were derived from medium to high grade metamorphosed terrain of Central Crystalline Gneissic Complex (CCGC) of the northern Sikkim. Presence of goethite in the sample indicates chemical alteration as well.

IV.1.5a. Mineral assemblage recorded in finer size fractions of the glacial sediments also indicate contribution is mainly from physical weathering process rather than chemical weathering.

IV.2.1. Nature of sediments provide basis for understanding the environmental conditions under which the sediments were transported and deposited in geological past.

IV.2.1a. The alteration of sediments occurred due to changes in river water flow, level of water, weathering and erosional events.

IV.2.2. Teesta River originates from different glaciers in northern part of Sikkim and the state lies in the upper basin of Teesta river. A small portion of the study area falls in the Darjeeling Himalaya as well. On the basis of geological formation of the Himalaya, the study has been divided into three stretches viz. upper stretch, middle stretch and lower stretch.

IV.2.3. Total twenty samples of channel sediments were collected from Teesta river in Sikkim- Darjeeling Himalaya. Six samples are been taken from upper stretch, eleven from middle stretch and three samples were collected from lower stretch.

IV.2.3a. The bulky samples were reduced by coning and quartering methods and 100g of weighted samples were poured into the sieve.

IV.2.3b. Samples were dried at room temperature and around 30g of sample of mesh size above 50 ASTM has been taken for grinding into Planetary Ball Mill Grinding Machine.

IV.2.3c. Petrographic study has been made by using thin sections prepared from sediments collected from the sample sites. Sediments of 80 mesh size separated for preparing the slide.

IV.2.3d. Further, the mineralogical study of slides were conducted under microscope magnification 4X and model analysis plotted by using point counting methods manually.

IV.2.4. The mineralogical variation of channel sediments in the basin using glacio-fluvial sediments shows that the mean grain size varies from coarse to fine from source area but it shows coarse sand to fine sand.

IV.2.4a. The channel flow deposit constitutes relatively moderately sorted to moderately well sorted sediments and clast-supported gravel with coarse to fine sand matrix.

IV.2.4b. Therefore, wide variation in sediment characteristics has been observed downstream of river Teesta. This variation may be due to tectonic influences in the area and human interference.

IV.2.4c. The X- ray diffraction analysis infers major mineral present in the sediments are mostly silicate minerals like Quartz, Orthoclase, Garnet, Anorthite, Calcite, Albite and clay mineral i.e. Illite and Illemnite.

IV.2.4d. Presence of Illite and Illemnite clay minerals suggest occurrence of chemical weathering as well. The abundance of Feldspar grains is relatively low in comparison to Quartz minerals.

IV.2.4e. Dominance of silicate minerals at most of the sites indicate metamorphic provenance. Presence of Ilmenite, which is chemically ferrous titanate ($FeO.TiO_{2)}$, makes it highly resistance to weathering and it is present in upper and middle stretch of study area. Thus, physical as well as chemical weathering contribute to sediment production.

IV.2.4f. The petrographic study reveals that the grains are more angularity in the higher altitude area, to sub-angular in lower altitude.

V.1. Sediment transport and grain size, depends on a number of factors; some of these includes- precipitation, discharge amount and its velocity, magnitude of human impact, topographical and geomorphic features of the terrain, basin geology, as well as the amount of load of sediment the river can carry.

V.1a. The Himalayan mountain system is considered to be world's most erosion prone region. The runoff of the Himalayan catchments is greatly influenced by the monsoonal rainfall.

V.2. The discharge and suspended sediment study is conducted in upper part on Sebu *Chhu* river catchment of Changme Khangpu basin where total area of this glacierized catchment is around 48.16 km^2.

V.2a. The catchment area covers Changme Khangpu and three other glaciers which is ultimately contributing to the Lachung *Chhu*, a tributary of river Teesta and lifeline for the people downstream in Lachung village.

V.3. The dynamics of flux of suspended sediment concentration and its relation to the discharge build with the help of rating curve developed for ablation season show very good correlation of discharge with suspended sediment load.

V.3a. Studies in different parts of the Himalaya show similar kind of results, i.e. a positive relation between discharge and suspended sediment concentration and suspended sediment load.

V.3b. Diurnal estimated SSC shows a poor relation with discharge while the SSL shows a significant relationship with the melt-water discharge in the catchment.

V.3c. The SSL and SSY in the study area have shown a decreasing trend from 2017 to 2018 in ablation season. Whereas, the trend is reported to be increasing in other parts of the Himalayan region including the Karakoram Range.

VI.1. The snow and glacial melt run-off study is vital aspect for avalanche forecasting, environmental impact, estimating potential of mini and micro hydro-power plants and to understand the hydrology for water resource management.

VI.2. The MODIS 8-day composite TERRA products have been selected for the study of snow cover variation in the Changme Khangpu basin from the year between 2002 and 2019. ASTER GDEM has also been used to study altitudinal variation of snow cover area in every month.

VI.3. The maximum extent of snow cover area was in February 2003 ~92.8 % of the total basin area (737.36 km^2) and minimum in November 2017 around 34.95 % (276.81 km^2).

VI.3a. The influence of Western Disturbances in the basin exists which contributes higher in the months between February-March.

VI.3b. In higher altitudes of the basin, there is continuous snow precipitation from January till the end of April. Whereas in the Western Himalaya the SCA shows declining trend from March onwards.

VI.3c. It also indicates pattern of snow accumulation and ablation is different in the Eastern and the Western Himalaya.

VI.3d. It starts decreasing from April onwards with the lowest snow cover area in the month of June 46.71 ± 5.24 %, July 34.17 ± 5.83 % and August 38.23 ± 6.52 %.

VI.3e. Mean annual SCA was highest in 2003 (67.46 ± 10 %) and lowest in 2017 (54.21 ± 9.1 %). Decrease in winter seasonal snow (January, February and March) in the year 2017 resulted in lowest mean SCA in this particular year.

VI.3f. Higher fluctuations in snow cover were observed in the accumulation period because of the frequent snowfall and melting at lower altitudes. The study also shows that snow cover area in accumulation period is decreasing while it is showing increasing trend in ablation period.

VI.3g. Maximum temperature is observed in the month of July which fits well with the minimum extent of snow cover in the same month.

VI.3h. Monthly trend of SCA shows decrease from April onwards with the increase in temperature of the region and it contributes continuously to snowmelt runoff in the basin till August.

VII.1. Therefore, glacier mass balance assessment is crucial as it is a key indicator of glacier health and regional-scale climate change. The need to develop indirect methods for the study of mass balance is highly in demand, as the availing data through field glaciological method in the Himalayan terrains is difficult. The most striking indirect assessment of mass balance is to use the in-situ equilibrium-line altitude (ELA) or accumulation-area ratio (AAR) and specific balance statistical relationship.

VII.1a. A number of glacial morphological aspects such as glacier shape and size, hypsometry, and bed topography can be investigated using remote sensing based techniques, and these parameters can be used for understanding the glacier mass balance.

VII.2. Mass balance estimation was studied for Changme Khangpu Glacier in North Sikkim. The glacier ranges from 4806 to 5975 m a.s.l with a slope of <10°. The ablation area of the glacier is heavily debris-covered ~80-90% of the total area.

VII.2a. The study was carried out using remote sensing based ELA/AAR modeled estimation of mass balance. The ELA was derived from different sets of imageries namely- LISS-III, AWiFS, Landsat TM, Landsat ETM+, Landsat OLI, Sentinel-2A, between 2008 to 2019.

VII.2b. First, the ELA of Changme Khangpu Glacier have been marked; thereafter the AAR for the glacier was estimated using the derivation as: **AAR** = Accumulation area ⁄ Total glacier area. To scrutinize specific mass balance values for 2008 to 2019, two regression equation have been used developed by Kulkarni et al. in 2004 only for western Himalayan region and Pratap et al. in 2016 for entire Indian Himalayan region.

VII.2c. The results suggest that the specific mass balance derived using regression equation (i) (Kulkarni et al., 2004) is highly uncertain because of the fact that the model was developed using the in-situ data of western Himalayan glacier's only till the year 2004. On the other hand, comparatively good agreement using equation (ii) proposed by Pratap et al. (2016) has been observed as the second model was developed using the in-situ data of all the Himalayan glaciers till the year 2014.

VII.2d. Negative mass balance of Changme Khangpu Glacier have been observed, although the rate of retreat is less in recent years (2008-2019) because the ELA of Changme Khangpu Glacier is already at the higher position. As the Changme Khangpu Glacier is highly debris covered and avalanche fed, the fluctuation in ELA is found less in recent period and is maintained at particular altitude.

VII.2e. The AAR for Changme Khangpu Glacier ranged between 0.47 to 0.60, much higher as compared to the glaciers of western and central Himalaya. Similarly, the highest ELA mark observed for Changme Khangpu Glacier itself was between 5230 m a.s.l and 5335 m a.s.l, as compared to the other glacier in Indian Himalaya like- the higher ELA data series represents the Chhota Shigri (4855 to 5185 m a.s.l), Gara (5050 to 5300 m a.s.l) and other glaciers.

VII.2f. Since, the ELA of Changme Khangpu glacier is already at the higher position and it can be altered by avalanche as well, the melting of this debris covered Glacier may reduce in the coming years or near future.

VII.2g. Studies from different parts of the Himalayan region (Western-Central and Karakoram region) show that the mass balance estimation done using AAR technique by remotely sensed data can directly estimate total loss and gain in glaciers mass.

VII.2h. This study also reports that Changme Khangpu Glacier has experienced loss in its glacial mass over the period of 12 years, however the ELA of this glacier does not show much variation.

VII.3. AAR method provides better platform for the study of mass balance but with certain limitations. If the field based mass balance and AAR data are available for certain years, the mass balance for subsequent years of the same glacier with the help of AAR derived from remote sensing method can be done easily and continuous monitoring is possible.

VII.3a. Remote sensing based study needs further parameters like- ELA (elevation), AAR and glacier density and thickness to estimate mass balance. The optical data in the mountainous regions suffers mainly from high cloud cover and shadows, with the snow covered topography which makes its use limited.

The Himalayan regions show a range of variations in local and regional climate pattern which makes difference in behavior of glaciers from one part of the Himalaya to other. Few glaciers in the Karakoram range in particular and in the Western Himalaya in general shows gain in its mass while most of the glaciers terminus and total area are receding in the western, the Central and the Eastern Himalayas. Linkage between grain size composition, textural and mineralogical characteristics of the Changme Khangpu Glacier of North Sikkim shows coarser as well as fine size fractions in variable proportion. Sorting of the sediments varies widely between poorly sorted to moderately sorted, thereby indicating glacial and glacio-fluvial processes were operational over the area. Natural processes and anthropogenic activities such as construction of dams on the river Teesta significantly affect sediments characteristics.

Geomorphic mapping is one of the mode of examining surface and sub-surficial terrain features and for understanding the surface processes, relief configuration, landscape evolution as well s subsurface composition.

Average rise of the ELA in Sikkim stands at 47 meters. The rise in ELAs 200-300 meters on one hand considers that climate is changing in this region. On the other hand, there would also be considerable amount of accumulation for sustenance of large ice bodies, considering that ELAs of the Himalayan Glaciers are above 5000 meters. As compared to the Western Himalayan region, triple precipitation regime in the Eastern Himalayan region would always provide a better input.

The glaciers usually retreat when their terminus does not extend. Qualitative assessment of rate of glacier retreat can be estimated by measuring the increase in length and height of moraine ridges as the sediments which were initially locked up in the glaciers now get accumulated on the sides of its flow-path. Greater the rate of glacial retreat more is the amount of sediment deposited. Receding glaciers may affect the water security in near future of the region.

The monthly trend of SCA starts decreasing from April onwards with the increase in temperature of the region and contributes more to snowmelt runoff in the basin till August. Pattern of snow accumulation and ablation is different in the Eastern Himalaya as compared to other parts. Variations in the amount of snow over peaks are observed over the Himalayas (Western, Central and Eastern Himalaya); it could be attributed to the upper air circulation and weather systems which influence the timing of maximum snow fall across different parts of the Himalaya.

Diversity in the local weather pattern, climatic regime as well as geology of the area are few of the means to contribute to the weathering and total sediment flux in a season. These factors also have implications on amount of total sediment load to be carried by the river in a basin. Long-term temporal variation of sediment load in a basin is of utmost importance for the settlements downstream and also for the management of hydropower projects in the region. Due to data gaps in the Eastern Himalayan region, trend of sediment flow and meltwater discharge is difficult to estimate while it is of high importance for the downstream areas.

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