# CHARACTERISING GLACIAL LAKES FOR POTENTIAL OUTBURST FLOODS AND ITS IMPACTS IN LAHAUL & SPITI: HIMACHAL PRADESH

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**DOCTOR OF PHILOSOPHY**


**VARUNI PATHAK**

**CENTRE FOR THE STUDY OF REGIONAL DEVELOPMENT**

**SCHOOL OF SOCIAL SCEINCES**

**JAWAHARLAL NEHRU UNIVERSITY**

**NEW DELHI 110067**


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जवाहरलाल नेहरू विश्वविद्यालय
**JAWAHARLAL NEHRU UNIVERSITY**
**Centre for the Study of Regional Development**
**School of Social Sciences**
**New Delhi-110067**

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## DECLARATION

I, **Varuni Pathak**, do hereby declare that the thesis entitled **"Characterising Glacial Lakes For Potential Outburst Floods and its Impacts In Lahaul & Spiti: Himachal Pradesh"** submitted to School of Social Sciences, Jawaharlal Nehru University, New Delhi, for the degree of **DOCTOR OF PHILOSOPHY**, embodies the result of bona fide research work carried out by me. No part of the thesis has been submitted to any other university/institution in part or full for the award of any other degree or diploma.

Varuni Pathak

VARUNI PATHAK
(Candidate)

It is hereby recommended that the thesis may be placed before the examiners for evaluation.

**Forwarded By**

PROF. MILAP CHAND SHARMA
(Supervisor)
CSRD/SSS
JNU

Centre for the Study of Reg Dev.
School of Social Sciences
Jawaharlal Nehru University
New Delhi-110067

PROF. SEEMA BATHLA
(Chairperson)
CSRD/SSS
JNU

Chairperson
Centre for the Study of Reg Dev.
School of Social Sciences
Jawaharlal Nehru University
New Delhi-110067

*Dedicated*

*To*

*My Family*

# ABSTRACT

Glaciers are one of the key indicators of Climate Change which respond to miniscule variability in weather parameters, faster than any other medium that can be measured within a short span. These ice bodies have waned and waxed during the geological history, leaving behind mesmerizing landscapes, e.g., the Higher Himalaya. Comprehensive studies on the Himalayan glaciers have remained limited, except for perfunctory references due to the inaccessibility and large areal extent. Glacial landscapes, once rightly identified, bear a gift in unraveling the rates of both the oldest and youngest phases of growth and decay of glaciers, as a result of cooling and warming of the Earth's land surface. In India, multiple episodes of waxing and waning of glaciers, source of perennially rivers, have helped the formation of several glacial lakes. Due to increase in the rate of melting of the glaciers, the lakes are increasing in areal extent and water stored in such lakes, along with the increase in number of new lakes in recent decades. These lakes are known to breach once the resistivity threshold of blockade holding lake water is reached, resulting in devastating glacial lake outburst floods downstream, popularly known as GLOFs. Such breaches can occur in either of the situation, whether glaciers wane or wax. In order to develop mitigation plans and policy measures from environmental hazards; GLOF analysis has been conducted for the state of Himachal Pradesh, particulary in Lahaul & Spiti for its highly glacierized administrative units. The climatic change/variability in recent decades has aggravated impacts on the glacier environment in the Himalayan region. Fragile natural set up has been compounded by human influence through increased infrastructure development in these ecologically sensitive areas. There is an imperative requirement for accurate, precise, and continuous monitoring of the glaciers and glacial lakes in order to formulate risk reducing measures. The variability in snowfall, rainfall and occurrence cloud-bursts, along with increase in snow & glacier melt-waters pose threat to the existence of many settlements in the mountain regions along river courses because of GLOF. Flood inundation for hazard assessment and disaster management is a necessary thing to do along with understanding the dynamism of glaciers and glacial lakes. Therefore, the present study is aimed to understand the increasing threat of GLOF and its associated impacts.

Lahaul & Spiti is a unique socio-physical unit of Himachal Pradesh. It is enclosed by high mountains on all sides and thus making a closed physical unit. There is a great deal of physical (topographic) diversity, of which the most striking features are the high mountain ranges and deep narrow river valleys. The ranges rise to a mean elevation of about 5400 meters above the sea level. This study areas winter precipitation in the form of snowfall through mid-latitude westerlies while in some limited rainfall through Indian summer monsoon. The study area is reservoir of perennial glaciers of varied, type and size. Given the richness of glaciers and associated features, it makes an important study area to analyze glacial related hazards. The present study aims to prepare the inventory of glaciers distributed in Himachal Pradesh across different basins. The study tries to present an inventory of glacier distribution according to its size, area, altitude, aspect and slope. This study also aims to understand the changes in the accumulation and ablation extent of the glaciers through ELA. Because ELA depicts the mass balance of a glacier. This aids in understanding the distributional pattern of the glacial lakes. Further, glacial lake inventory for Lahaul & Spiti has been done. Glacial lakes are classified into five broad categories which are moraine, supra, valley, blocked and pro-glacial lakes. Glacial lakes are distributed at different altitude range with maximum percentage of the glacial lakes between the altitude ranges of 4500 meters to 5500 meters. In total, there are 63 glacial lakes in Lahaul & Spiti. In terms of area, glacial lakes are of varying size. The smallest lake is 0.001 $km^2$ to the largest glacial lake with an area of 1 $km^2$. The size of the glacial lakes has a topographic control and also the source glacier dynamics. This entire work has been done through secondary data sources. All the glaciers and the lakes were digitized from the Google Earth Pro for Lahaul and Spiti district of Himachal Pradesh. For comparison between Lake Boundary and amount of permanent snow cover over three decades, Landsat images were used. The images were used from USGS Earth Explorer. SRTM 30 meters was also used.

Chenab Basin houses the maximum number of large glaciers (exceeding 10 $km^2$,) while the largest in the basin include Bara Shigri and the Samudra Tapu glaciers. The ratio for the estimation of ELA has been taken as 0.48. The maximum average Equilibrium Line Altitude in the glaciers in the year 2000 was noted to be 5576 m while the lowest was noted at 4641 meters AMSL respectively. In the year 2016, the highest estimated ELA was noted at 5541 meters and the lowest at 4663 meters

AMSL. The median value of change in ELA is 0 which means that most of the bigger glaciers in the valley are stable according to their mass balance. Considerable numbers of glaciers in the Chenab basin have shown no changes in their area. Most of the bigger glaciers in the valley reflect considerable glacier cover. There are two most vulnerable lakes identified within Chenab basin in Lahaul & Spiti region. These are Sissu and Samudra Tapu glacial lake. These are identified as potentially dangerous glacial lake. This is done using the reference work from previous studies. Both the lakes have been mapped and analyzed along with their parent glaciers from 1972, 2001, 2010 and 2020. In the year 1972, total glacier area of the Sissu was 27.991 sq. kilometer. In 2001, it decreased up to 25.7 $km^2$. Decadal decrease rate of the glaciers in the Sissu watershed from 2010 to 2020 is abnormally high at a rate of -10.914 $km^2$, and reduced up to 23.18 $km^2$. Decrease in glacier and seasonal snow cover is a factor responsible for increase in lake area and volume. Sissu lake area that was 0.199 $km^2$, in 1972 increased to 0.46 $km^2$, in 2001 and 0.59 sq. km in 2010. From 2010 to 2020, at a rate of 57.62% lake area increased to 0.93 $km^2$. In case of Samudra tapu watershed, glacier area decreased to 88.9 $km^2$, from 91.34 $km^2$, from 1972 to 2001 (within span of 28 years). From 2001 to 2010 there is again an increase in glacier area similar to the Sissu watershed. While from 2010 to 2020, there is a sharp reduction in glacier area to 68.64 $km^2$. Samudra tapu glacial lake area was 0.3 $km^2$, in the year 1072 which increased to $km^2$ sq. km in 2001, 0.98 $km^2$, in 2010 and presently is 1.39 $km^2$, in 2020. After extracting the lake area through satellite images, volume of the lakes have been calculated using empirical methods formulated by Fujita, Huggel and Chaohai. There are stark difference in numerical values of volume through different formulae as the formulae were developed using specific areas. Due to difference in numerical constants, the values are different.

Hazards of any intensity and magnitude is dangerous for mankind. Disasters lead to loss and destruction such as number of human lives, physical and economic infrastructure psychological and social cultural loss. Therefore, the next step is the hazard vulnerability assessment to minimize the wrath of disaster in case of GLOF. Economic cost estimation in case of the disasters in an important aspect of this study. There are 5 thematic layers used as a raw material or base maps for the final creation of vulnerability assessment map. The data sets used are ALOS PALSER (DEM) with 12.5 meters for the study area collected from the USGS. Food inundation map prepared by HEC-RAS software as one of the layers. LANDSAT 8 image is used to create LULC for the catchment area. Primary data from the field to estimate economic loss within inundated area. There are 279 people that are at the risk of losing their lives in case of GLOF, out of which 91 make the dependent population. There is 98 active male working population that is a part of active and working economy. Additionally, there is a young population of 80 children. In terms of physical infrastructure, the loss is would be huge. There are 25 houses that might get demolished. Critical infrastructures such as one government school, one government hospital, one Public Works Department Office are also under threat. The Sissu Bridge and the national highway is also under threat in case of a GLOF. Out of total length of the highway crossing through the Sissu watershed, 4 kilometer stretch is likely to get destroyed. Total monetary loss value of all the infrastructures is huge which stands close to 3,430,748 USD cumulatively from construction, agriculture, economic and social infrastructure. There are other serious loss that cannot be quantified. These are social, cultural, physiological and psychological loss. Disasters leave an everlasting mental and emotional trauma on the people. It takes several years for the victims to come out of this trauma. Loss in their mental and emotional health diminishes their work potential. It takes several years for the peoples to heal from the loss of their loved ones and their houses. This can make many mentally unstable. Their coping mechanism can push many of them into anti-social practices. This further affects their physiological health too. Children who would spend their childhood in school spend their formative years in the recovery from such disasters. This also has a negative impact on the socio-cultural lives. Inter-personal relationships also get adversely affected.

In brief, this study highlight the dynamics of the glaciers and the glacial lakes. This is an attempt to present the contemporary inventory of glacial lakes, its area, size and volume. This spatio-temporal dynamics of the glacial lakes highlight the dynamic glacial environment and increasing threat of GLOF and changes with the continuing of such trend. It also highlights the increasing human encroachment and interventions in ecologically fragile mountainous regions and its adverse consequences. This study is an attempt to highlight the importance of vulnerability assessment in case of the GLOFs and suggest appropriate measures to reduce the loss and destruction antipicated by GLOF within the study area.

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Date

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# CONTENTS

**CHAPTER 6**



**CHAPTER 7**

# LIST OF FIGURES

# LIST OF TABLES

# LIST OF PLATES

# LIST OF ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| AAR | Accumulation Area Ratio |
| AMSL | Above Mean Sea Level |
| ASTER | Advanced Spaceborne Thermal Emission and Reflection Radiometer |
| GDMV2 | Global Digital Elevation Model Version 2 |
| AWM | Area Weighted Mean |
| DEM | Digital Elevation Model |
| E | East |
| ELA | Equilibrium-Line Altitude |
| ETM+ | Enhanced Thematic Mapper Plus |
| FCC | False-Color Composite |
| GIS | Geographical Information System |
| GLOF | Glacial Lake Outburst Floods |
| GPS | Global positioning System |
| GSI | Geological Survey of India |
| IPCC | Intergovernmental Panel on Climate Change |
| LGM | Last Glacial Maximum |
| S | South |
| SE | South East |
| SRTM | Shuttle Radar Topography Mission |
| SW | South West |
| TM | Thematic Mapper |
| UTM | Universal Transverse Mercator coordinate system |
| USGS | U.S. Geological Survey |
| WGS | World Geodetic System |

# CHAPTER 1

# INTRODUCTION

## 1.1 INTRODUCTION

Climate change is one of the most contentious and debated topics of the 21st century. It is commonly believed that human-induced climate change has been altering the natural environmental setting. Of late cryosphere and the Himalayan Mountains have become the most important and widely discussed topics in terms of climate changes. (IPCC, 2007a; Raina, 2009). The rise of temperature noted in the Himalayas is higher than the global average, and therefore, it is perceived to bear a significant effect on the cryosphere (Eriksson et al., 2009). Climatic changes in the high mountains bear varying effects on the dynamics of the cryosphere and glacier variability (Haeberli and Hoelzle, 1995). A slight increase in ambient temperature in the high mountains region has the potential to accelerate melting, which results in a negative mass balance causing the glacier retreat (Kulkarni et al. 2005). According to peer-reviewed and published reports, this has led to the retreat of several glaciers even in the non-polar regions. The Himalayan region is going to be the worst affected, given the various levels of dependence of the population in the region where its meltwater drains into.

India is home to scores of high altitude glaciers, sources to major perennial rivers running a life of ¾ that of the Indian population. It is rightly considered that the mountain environment is an arduous region for human settlement. This situation is further being aggravated because of reckless anthropogenic activities. This external force in the form of anthropogenic activities is leading to widespread disturbances of the homeostatic setup of mountain regions. This is leading to the melting of glaciers. Glacial dynamics is closely related to the formation of glacial lakes in a variety of ways. A glacial lake can be described as a volume of water present nearby glaciers. It could be on, at, besides, sides, nearby, or in front of the glacier. Due to the increasing pace of melting of the glaciers, size, extent and volume of the lakes are continuously increasing beside the formation of other contemporary lakes. These lakes are known to breach, once the resistivity threshold of the blockade holding lake water is reached. This results in devastating glacial lake outburst flood downstream. An instantaneous and quick downpour of a huge amount of the water volume embedded with sediments and debris content is called Glacial Lake Outburst Floods (GLOF). Breaches may occur when the glaciers wane as well as wax. There can be several mechanisms or factors responsible for the lake outburst. Some of the major factors responsible for the breach of the lakes are: avalanches, melting of ice crystals present within the dam materials, earthquake, landslides, and sudden influx of water supply in huge quantities to the lakes either through glacial melting or cloud burst. Freeboard dismantling due to tectonic events that leads to breaking up off moraine dams. Glacial lake outburst is always catastrophic when melting is rapid either for anthropogenic or natural reasons, causing lake waters to swell and build up the pressure on retaining materials of the dams, holding the moraine-dammed pro-glacial lakes. The moraine- dammed lakes are susceptible to failure owing to unconsolidated material and unsorted building structures. Such glacial lakes can result in infrequent glacier lake outbursts draining out as cascading floods (Mergili & Schneider, 2011). It is regarded as one of the most important glacial borne hazards causing huge destruction damage potential (Osti & Egashira, 2009). For a better understanding of the potential for GLOF's glacier dynamics over time and space is important to evaluate.

Several scientific reports have highlighted that number and size of the glacial lakes are on the verge to increase likely due to global warming. Glacial Lake Outburst Floods (GLOF) have cross-border wide ranging destructive impacts in terms of human lives, social, economic, and other physical infrastructures. To avoid this calamity, it is extremely important to have a constant monitoring and evaluation of the glacial lakes. This makes a way for sustainable early warming mechanisms and mitigation measures in the glacial regions. (Bajracharya, 2010). The aim of the study should also be to assess and measure the vulnerability of the locals and in terms of their risk capacity and the likelihood of a probable event to assure timely evacuation and rehabilitation.

This study focuses on the Himalayan states of the Union of India at large, the Himachal Pradesh. The upper catchment of these rivers, important for countless lives in North India, observes the manifestation of snow in the Accumulation season when precipitation occurs in the form of snow. The Himalayas range from the Nanga Parbat at the northernmost bend of the Great Indus to Namcha Barwa, little to the west of the Yarlung Tsangpo of the upper Brahmaputra catchment take a syntaxial bend towards the south. The vast diversity of orientations of the mountain ranges reveals the history of the contact of the Indian terrane with the Eurasian plate roughly 10 million years ago. The impact of the collision differed according to the direction of thrust, giving rise to a vast array of landforms that we presently behold in the Himalayan region. The upheaval of this young fold mountain system has been vital to the development of the current observable climatic regime of India. In many ways, the Himalayas form a zone of transition between the Indian monsoon system and the central Asian climatic regimes. While some regions of the Western Himalayas are under the impact of the summer monsoon and some by the Mid-Latitudinal Westerlies. Throughout its geological history, the Earth has witnessed a dynamic range in climate on the spatial and temporal scale with different frequencies and magnitudes. The rate of change has varied, with long periods of gradual and subtle transformation punctuated by major upheavals. The earth is somewhat imperfectly understood, scientists and researchers are barely beginning to comprehend the multiple feedbacks that exist in the system. Glaciers form an important components of the cryosphere.  It covers about 10 percent of the surface area of the Earth and is primarily common to high latitudes and high altitudes (Raina, 2009). The Himalayan and the Trans Himalayan glacial systems have occupied a 50 percent area of the glacier outside the polar realm (Wissman, 1959). The Hindukush-Karakoram-Himalayan (HKH) region is the richest glacier region after the polar realm and is often referred to as the Third Pole of the world (Owen and Dortch, 2014).The Himalayan Alpine glaciers constitute an open system possessing an annual input (accumulation) and output (ablation), the magnitudes of which are determined by the interaction of mass and energy of the glacier system with atmospheric components (Raina, 2009).

Glacier dynamics throughout the Hindukush Karakoram and Himalayan regions are dissimilar to each other because of regional as well as local scale topographic controls, which largely control the dynamics of individual glaciers. This results in differential response rates across the HKH at differential Spatio-temporal scales. Many parts of the Himalayan have experienced the loss of glacier ice mass since the 1960s. The extensive spatial research on the HKH, through remotely sensed data, reported that Sikkim observed the highest glacier recession followed by the Himachal Himalaya and the Karakoram and for the period of 2000/01/02 and 2010/11 (Bahuguna et al., 2014). Although the study carried out by Hewitt, 2005, address the condition of expanding glacier within the Karakoram ranges. The Khatling glacier in the Garhwal Himalaya has been reported retreating at an alarming rate of -88 m/y (Raj et al., 2017. The in-situ measurement of the Dokriani and the Chorabari glacier of the Garhwal Himalaya was reported to have experienced a faster rate of snout recession with a rate of 6.8 ma-1. Simultaneously, glaciers in the East Karakoram Himalaya were advancing during the last decades, such as Aktas (+66 ma-1), Kichik Kumdan (+6 m-1) (Bahuguna et al., 2014). The variability in the glacial dynamics depends on a multitude of geomorphic factors that influence microclimatic variations within sub-watersheds. Amongst them are Elevation, Geographic location, Angle of slope and Aspect of the glaciers, etc. These factors influence the working mechanisms of the glaciers as well as decide for the amount of insolation and duration of sunlight received, which may have a more prominent role on the glaciers than generalized datasets. Glacier's size, prevailing slope, glacier altitude, etc. govern the rate of the glacier recession in response to the climate shift. Debris cover on the glaciers also induce considerable influences in the dynamics of the glacier. The higher proportion of the debris on the debris-covered glaciers insulate glacier ice from melting in one hand, and on the other hand, helps the formation of a supra-glacial stream or pond that aids the melting of glacier ice.

The glaciers in the Himalayas have asynchronously advanced with the Northern Hemisphere ice sheets. Glaciers in the HKH region are more sensitive to intense Indian summer monsoon (ISM). The assumption therefore is; due to the locking up of huge amounts of water in ice sheets, the HKH region showed limited glacial expansion attributed to limited precipitation in the Global Last Glacial Maximum in 26-19 ka; although, some glaciers in the Himalaya did advance during the Glgm (Owen et al., 2009; Richardson et al., 2000). Furthermore, monsoon activity is determined by large scale factors like insolation over Tibetan plateau, Global Circulation Model (GCM), the variability of the Indian Ocean sea surface temperature (SST), meridional or cross-equatorial temperature and pressure gradient, Obliquity factors, etc. which influences the local climate the climate vis-à-vis glacier.

Several new glacial lakes have come up within the Himalayas owing to the retreat of the recession of many glaciers. Glacial lakes are a litmus test of the glacier dynamism. (J. Gardelle, E. Berthier, Y. Arnaud, 2013) and unsteady lakes can pose hazards to locations within the valley region. Glacial lake outburst floods drain as hazardous and threatening floods within seconds of its origin. It is a disaster killing thousands of people in different regions across the globe (Richardson & Reynolds, 2000). Many such events have occurred in the Himalayas (Osti & Egashira, 2009). Thereby, GLOF associated risks have been receiving more and more attention by the academia, scientific community and the policymakers for preparedness measures.

Because of this increasing threat of global climatic changes and warming, many more such glacial lakes are likely to come up. Thus, it is highly imperative to understand, assess and analyse the threat potentiality of these “risky” glacial lakes, which may lead to such hazards in near future. The maximum level up to which these moraine-dammed lakes can hold on to glacial meltwater depends on their material composition, particle size, height, width and other geometrical parameters (Korup & Tweed, 2007). Failure of moraine dam leads to a downpour of lake water when the pressure of lake impounded water exceed the holding capacity of the moraine dams. This again exceeds by the displacement water waves and constant slow steady seepage of the water waves (Korup & Tweed, 2007). Overtopping flow can also be caused after sudden supply of water in the glacial lakes due to cloud bursts or the sudden melting of parent glacier sources. At the same time, mass movements that are ice avalanches, rock-falls, debris flows or landslides, etc. generate displacement waves.(Clague & Evans, 2000) .These displacement waves once generated lead to erosion or dismantling of the moraine dams. This again generates more secondary water waves, embedded with the dam materials, boulders and other sediments carried to downstream areas. These irreversible processes drains out the glacial lakes.

Therefore, glacial lake inventories are a must to identify the vulnerable lakes for further research and analysis to avoid such unforeseen disasters causing havoc to human societies (Allen et al. 2009).

## 1.2 LITERATURE REVIEW

Scientists from different geophysical fields, especially, glaciologists, have put up a series of detailed and comprehensive research work on glacial hazards specifically on GLOF. These researches are focussed on the Himalayan glaciers but focus mostly outside India. Some of the pioneering works are summarized here.

In the 20th and 21st centuries, the world's glaciers have receded due to increased ablation. This issue has received serious attention from several native and international scientist groups. The Himalayan glaciers are more prone to this issue because these glaciers are receding much faster in comparison to the rest of the world (International Commission for Snow and Ice report by the Working Group on Himalayan Glaciology). Glacial borne hazards have further grabbed the attention of the scientific community primarily because of two reasons viz: a threat to human life and damage to costly mountain infrastructures such as hydroelectric power plants and highways This is getting worse in the current century because of the intrusion of human activity into the natural setting of the glaciered mountain regions (Richardson & Reynolds, 2000). This intrusion and extension of human activities in the high alpine regions have been rapidly aggravating the already fragile situation of glacier hazards (Richardson & Reynolds, 2000).

The "Glacial hazards" has been defined by Richardson & Reynolds (2000) as any glacial borne or glacial associated incidences, process, or phenomenon that adversely affects the human life and activities from glacial hazard. During the entire 20th century glacial retreat was seen on a large scale that led to the formation of precariously positioned glacial lakes, particularly between the moraines brought down and deposited by the maximum glacial extent during the Little Ice Age or the previous Holocene cold periods. Besides, in the recent past, glacier fluctuations greatly influenced the development of new glacial lakes (Hoelzle, 1995). Glacial hazards particularly GLOFs are very much important to analyse, assess and study because outbursts of these lakes creates havoc to life (Richardson & Reynolds, 2000). In the recent past, commercial activities have taken a large shift into the high alpine areas prone to glacial hazards.

GLOF is one such hazard that has quite a different nature in terms of mechanism of occurrence, location, bursting mechanism and reach.  Thus GLOF has been dubbed with varied nomenclature depending upon the lake source, such as moraine Dam Lake or ice Dam Lake. Several glacial and geomorphological factors that affect the occurrence of GLOF events. Lake water level fluctuations, seepage, glacier movements etc. vary with seasonal climatological and hydrological conditions. The geomorphological setting of glacier lakes and their hydrological behaviour are important general indicators in comprehending glacier lake stability because it is only the unstable lakes that outpour leading to a GLOF event. Besides, hydro-geo parameters, types, and locations of glacier lakes also decide the stability conditions of the lakes.

Moraine-dammed and ice-dammed lakes are widely different from each other. Ice-dammed lakes undergo seasonal cycle of filling and emptying .Moraine dammed lakes do not get refill instantly after it gets drained out. The Himalayan region has more moraine dammed glacial lakes than the ice dammed ones, more than any other regions of the world. This is because the Himalayan glaciers produce large debris that eventually culminates into the large lateral, end and, terminal moraines. The Glacial lakes associated with cirque glaciers and old stabilized moraines of the Pleistocene period are considered to be less hazardous than the rather contemporary lakes post "Little Ice Age".

The bursting mechanism and processes for GLOF events are so complex that it is difficult to assign to one single factor or particular GLOF event. It is because the bursting process is not just dependent on the lake and dam conditions, rather the wider surroundings of the lake, for instance, glaciological setting of the parent glacier of the lake, slope stability of the moraines surrounding the lake (Vilimek et al. 2014). There have been several studies suggesting different mechanism of bursting of glacial lakes.

Heavy rains due to cloud bursts, calving at the snout of the glacier, avalanches, debris-flows or water influx to the lakes from the feeder glaciers can also cause glacier lake floods. Precise forecast of such an event is usually difficult (Frey et al., 2014). It has been argued that the ice avalanches are the most important and potent factors to cause outburst of the lakes. Richardson and Reynolds, (2000) through empirical observations of 26 glacial lake outburst floods in  the Himalayan region found out that 53% of them were initiated by the broken mass of ice avalanches falling into the lakes from the hanging and calving glaciers that leads to displacement waves.

As per the available studies and records, it has been established that the climate also has a major role to play in increasing the occurrence, frequency and, magnitude of the processes involved. The climatic change and variability in the recent past led to significant impact on glaciers particularly, on the Himalayan glaciers. It is because the Himalayan glaciers are geologically young fragile and vulnerable (Lama, 2009).

Richardson and Reynolds (2000) have listed three mechanisms for the glacier bursting process viz the breaking of the water pocket internally, the subsequent enlargement of internal drainage channels and glacier buyoncy, or 'acking', with sub-glacial discharge.

Schneider et al. (2014), in their study suggest that cascading mass movement processes for instance rock or ice avalanches are a major cause that impact glacial lakes and consequently trigger these causing a GLOF event with high amount of destruction downstream.

The breakdown of lake water holding dams can also lead to a major GLOF event. This breakdown of moraine dam has been attributed to a lot of factors. It can happen because of increased overflow from the lake during heavy rainfall period or because of overtopping of wave surge generated due to rock-fall, debris flow or piping (Gupta, 2013)

GLOF events are one of the deadliest hazards possible having a trans-boundary impacts leading to a great loss of lives and infrastructure which is why early warning systems, as well as mitigation measures, are required in vulnerable areas after having detailed mapping of such lakes. Amidst rapidly occurring changes in the remote, inaccessible glacial and periglacial environments due to climatic changes, it needs a continuous updated and validated information base. Due to the dynamic nature of formation and growth of the glacial lakes, quick and frequent collection of data is therefore necessitated.

To investigate the hazard potential of such lakes and to prevent the hazard level of the sudden and catastrophic discharge, a continuously monitored, detailed and accurate inventory of glacial lakes is required. Though modern-day technologies of remote sensing and GIS may be fruitful in monitoring the dynamic glacial lakes and alongside assessing the potential damage, it is extremely difficult to predict the future timing of the events.

The major issue with the hazard assessment of GLOF events is the identification of the glacial lakes. Because of their remote and distant location, there is insufficient glacial lakes inventory. This problem is grave particularly in Himalayan regions (Richardson and Reynolds 2000). It is not possible for anyone to manually identify and map all the glacial lakes in such inaccessible and difficult rugged terrain. Remote sensing coupled with Geographic Information System is, an extremely important tool to not only map but also to monitor the changes in glacial lakes (Huggel et al.2002).

ICIMOD in association with researchers of different countries prepared a glacial lake inventory for the Himalayas from 1999 to 2005. Many scientists, as per the data available and their objectives of the study, used different remote sensing and GIS method to monitor and map glacial lakes. For instance, Bolch et al. (2008) attempted an automatic detection method of glacial lake using a Normalized Difference Water Index (NDWI) on Imja a Glacial Lake. Gardelle et al. (2011), carried out the transboundary assessment of glacial lake distribution. Teiji Watanabe(1994), has analysed the prospects of a GLOF event in the Khumbu Himalaya based upon the information on steady increase in the volume of the glacial lakes.

In order to estimate the discharge, only empirical methods were used by the scientists. Raj (2010) used empirical methods to estimate peak discharge flows in the Zanskar basin, Jammu & Kashmir. An empirical formula for the same purpose was also developed by Fujita et al (2013) to estimate the potential flood volume of the Himalayan glacial lakes.

Though it is not possible to predict the time of outburst or occurring of GLOF event even after using the remote sensing tools; it can be useful in identifying the mechanism of a trigger. For instance, displacement waves from avalanches induce Lake Outburst (Grabs & Hanisch, 1993). In this case, slope can be measured using multispectral satellite images. Interconnected lakes through a chain reaction mechanism, lead to outbursts of the other lakes lying in the same vicinity. Therefore, it is important to identify drainage paths between such lakes. This can be performed utilizing geomatic tools. Increased outpour or failure of a dam can also occur due to high precipitation and runoff. This can be assessed by studying and analysing the hydrological DEM of the catchment area of the lake. Remote sensing can be used to identify the blockages or the settlements on way to the flood path (Clague & Evans, 2000).

However, the methods of remote sensing and GIS have certain shortcomings, for which it is heavily criticized. For instance, lakes in glaciated areas are difficult to identify through satellite data because lakes show a huge amount of turbidity starting from light blue to green to black. This is because lakes are influenced by sediments, depth of the lake and the lake bottom characteristics along with lake origin. To correct it, Difference Water Index (NDWI) was formulated.

To analyse lake dynamics analysis, it is seen that GIS and remote sensing again have its limitations. Since lake area can be extracted from the remote sensing data sets but the lake volume cannot. To estimate potential peak discharge in case of the outburst knowing the correct lake volume values is a must. The accuracy of these lake parameters based on remote sensing depends on the relationship between water depth and the energy reflected by it (Baban 1999). This relationship is also quite difficult to establish in the high mountain regions. This is why empirical studies need to be done in such cases. Since precise calculations are difficult, these values can be obtained using indirect methods (Clague & Evans 1994). Clearke,(2003) again propounded an empirical relation to predict the peak flow from the volume of the lake to determine the threat level. These indirect methods cannot be established for moraine-dammed lakes due to a lack of data about dam height and width, which can be calculated using remotely sensed data. Therefore only an empirical relationship can be established between peak discharge and lake volume.

## 1.3 STATEMENT OF THE PROBLEM

Various recent studies show that different glaciers within Lahaul have experienced a distinctive rates of retreating, thinning of glaciers and, where glacier fluctuation caused the emergence of new lakes or expansion of existing moraine-dammed, supraglacial and proglacial lakes (Raina, 2009). Moreover past signature and remnants of GLOF event have been identified in the upper reaches of Chandrabhaga basin in Lahaul Himalaya.

It is also found that from 2010 satellite data, many newly formed glacial lakes in the Lahaul Himalaya have appeared than what was found by ICIMOD inventory in 2003. The faster rate of growth of lakes in the Chandrabhaga basin also indicates the possible development of the hazards. For this purpose, time series analysis in changes of the glacial lakes is very pertinent. Therefore, preparation of a current glacial lake inventory to find out the spatio-temporal dynamics of glacial lakes in the Chandrabhaga basin of Lahaul Himalaya is a must followed by systematic observation and assessment of lake expansion is essential for the hazard potential.

In the mountainous, steep and, rugged topography, most of the human activity and built-up area are continuously growing along the major rivers. Even many hydroelectric projects and barrages have been built on these rivers in the upstream as well as in the downstream areas. Thus, in the near future, any catastrophic events related to glaciers and glacial lakes, which have occurred in the past as well, will impose destructive effects on most of the human resources and property in Lahaul Himalaya. Hence, one of the most important tasks is to classify of those lakes properly to identify the most potentially dangerous glacial lakes which can create a hazardous event in the future to reduce the degree of probable damages. In this regard, the risk assessment of potential flood hazards is to be created by selecting potentially dangerous glacial lakes.

## 1.4 RESEARCH QUESTIONS

1. Is there any increase in the number and size of glacial lakes in the region?
2. Are these co-related with the dynamics of parent glaciers?
3. Given the existing infrastructure within the catchment what would be the extent of the damage?

### 1.5 OBJECTIVES

1. To map the glaciers in the Himachal Pradesh and the glacial lakes in the Lahaul and Spiti region.
2. To identify vulnerable glacial lakes and compare the Spatio-temporal dynamics of the selected potentially vulnerable lakes with respect to the source glacier.
3. To assess potential of the outburst of the selected vulnerable lakes.
4. To estimate the probable cost estimation of losses in the face of breaches and inundations downstream.
5.

## 1.6 STUDY AREA

Lahaul and spiti, the largest district of Himachal Pradesh attained the status of a district in the year 1960. Earlier it was a tehsil under Kullu sub-division in erstwhile Punjab (District Gazetteer, 1971).

It has two physiographic and cultural divisions which are Lahaul and Spiti. The Lahaul division of Lahaul and Spiti district of Himachal Pradesh has an extent from 32°8'N to 33°19'57" and 76°46'29"E to 77°55'E meridians. It has an estimated area of about 6849 sq.km. The maximum length is about 115.873 kilometres and maximum breadth is about 86.904 kilometres. Administratively, it includes the tehsil of Lahaul and sub tehsil of Udaipur.

The region is flanked by the Greater Himalayas in the north-east and Pir Panjal in the south-west. The boundaries between Lahaul and other regions are well delineated by the arêtes of high snow-clad mountain ranges. Chamba lies in the west, Kullu in the south-east, Kangra in the south, Zanskar in the north and, Spiti in the east. The region can be reached through the high mountain passes. The Baralacha Pass (4891.12 meters) provides the entry from Ladakh, the Kunzun (4419.6 meters) from Spiti while Sach Pass from the Pangi region of the Chamba district. But the most frequent access to the valley is through the Rohtang Pass (3977.64 meters).

Lahaul is a unique socio-physical unit of Himachal Pradesh. It is enclosed by high mountains on all sides and thus making a closed physical unit. Within Lahaul, there is a great deal of physical (topographic) diversity of which the most striking features are the high mountain ranges and deep narrow river valleys. The ranges rise to a mean elevation of about 5400 meters above sea level. Even the Chenab River is above 2164 meters at its exit from the valley. The entire area is much higher than its counterpart Kullu where Kullu is decorated by lavish green forests but Lahaul offers precipice cliffs and beautiful glaciers. The high peaks give the appearance of highly pinnacled topography. The Chandra and Bhaga, and Chandrabhaga after its confluence a Tandi, are the major drainage features in the study of the geomorphology of this region.

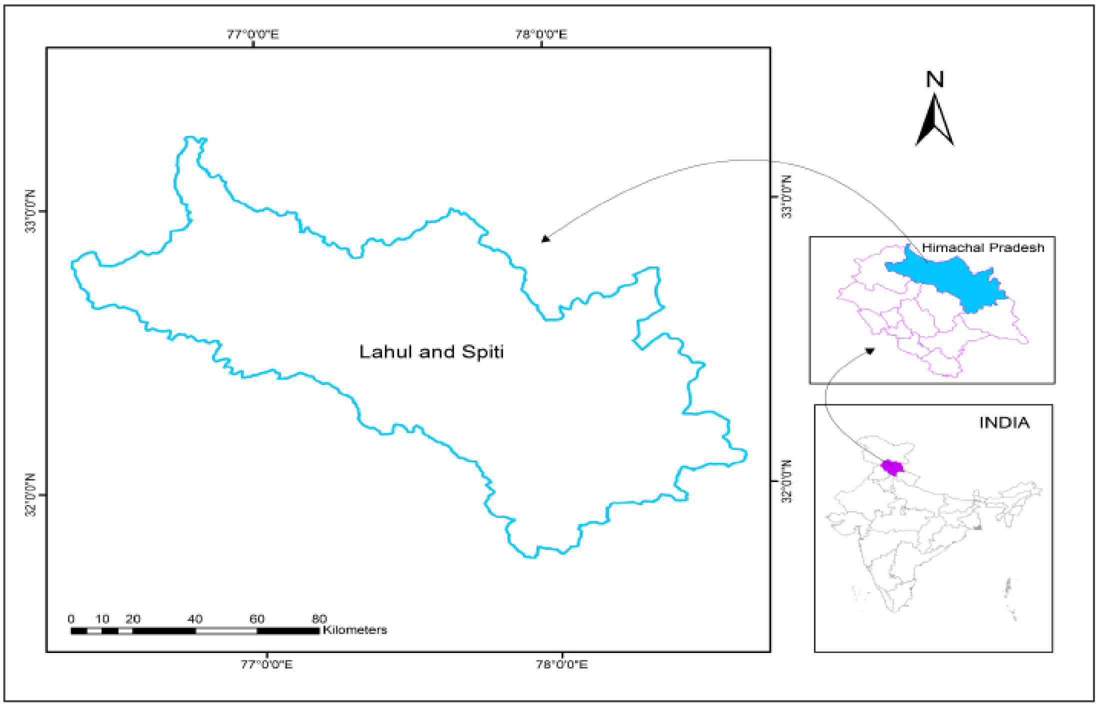



**Fig. 1.1 Study Area**

## 1.7 DATA REQUIREMENTS

***Primary data source:***

Field measurements using GPS, Total Station, Sonar and Photographs.

Infrastructural data viz: highways, hydel power projects through field surveys.

Agriculture data from field surveys.

Preliminary study of the villages under threat to assess the degree of loss in the case of probable GLOF disaster.

***Secondary sources:***

Survey of India toposheet- 1:50,000

LANDSAT MSS 30 meter resolution for 1972

LANDSAT ETM+ 30 meter resolution for 2000

LANDSAT 8 OLI 30 meter resolution for 2010, 2020

ASTER DEM 30 meter, ALOS PALSER DEM 12.5 meter

CORONA images FOR 1973

Google Earth images for different years

Weather data on rainfall, snowfall and temperature from India Meteorological Department (IMD) from 1998-2014

Land Surface Temperature (LST) from USGS Earth Explorer in Hierarchical Data Format (HDF) from 2010-2019

Population Tables from Village Directory 2011

Data on economics variables from District Census Handbook, 2011

## 1.8 METHODOLOGY

There are various digital tools used for the identification and delineation of glaciers and glacial lakes done along with visual identification manually.

The following methods and tools will be applied for collecting data, co-relate them and finding out the conclusion:

***Mapping and Change Detection of glaciers and glacial lakes***

Remote sensing satellite data has been used for the mapping and change detection of glaciers and glacial lakes as it is not possible to map all the glaciers and lakes in high altitude rugged mountainous topography through fieldworks. Therefore, using these data sets in ArcGIS 10 and ERDAS Imagine14 Imagine supervised, unsupervised as well as spectral ratio methods have been used for this purpose.

***Image Pre Processing and Data preparation***

- Radiometric, atmospheric and geometric errors are the three basic errors that will be corrected if necessary with the help of ERDAS Imagine software before proceeding further.
- In Lahaul, Western Himalayas receives very little precipitation which is why images from September and October month are taken with the least snow and cloud cover. Multiple data sets have been used for the precision and accuracy in mapping.
- Pre-processing and preparation of data sets for further analysis is done using ERDDAS Imagine. Multiple layers of different bands of an image is stacked, mosaicked and then the subset of the mosaicked images is done.

***Glacier Mapping and Change Detection***

To achieve to the first objective, the glaciers are manually delineated using SFCC with band combinations of red, near-infrared (NIR), and shortwave infrared (SWIR), and true-colour composite of red, green and NIR, of Landsat MSS/TM/ETM+ and LISS IV images. DEM (Digital Elevation Model) i.e. ASTER (Advanced Space-borne Thermal Emission and Reflection Radiometer) and SRTM (Shuttle Radar Topography Mission) of the study area are used to generate slope map for altitude information. A shaded relief map has been prepared from the SRTM DEM (90 m) to identify glacial features manually. Survey of India maps are referred to aid the process of identification, location, and interpretation of glaciers from satellite data sets. Boundaries of glaciers are visually identified and manually digitized based on the presence of “ice divides’ within the accumulation zone. (Basnett, Kulkarni, & Bolch, 2013). Various image enhancement techniques are also be used to delineate the glaciers from other features.

***Glacier Fluctuation in the Study Area***

For detection of recent glacier fluctuation, the following remote sensing methods will be used:

- ***Glacier’s snout position detection***: Change in the terminus points or snout position in different satellite images will be mapped over a period.

***Glacial Lake Mapping, Classification, and Change Detection***

Generally, glacial lakes are seen at the snout, on or at the glacier boundary. During the winter season, the upper surfaces of the glacial lakes freeze but again melt in the summer season. Therefore, summer data sets to be used for lake identification and mapping. Thus, glacial lakes get discriminated from the other features. Glacial Lakes are also manually identified and digitized.

- According to several studies, it is believed that shadowed areas get identified as glacial lakes. Therefore, a slope map (semi-automated extraction from DEM) is also used to aid the identification process of water bodies in this region.

***Glacial Lakes Change Detection***

Change in the areal extent of the lakes will be mapped temporally to assess the vulnerability of the growing lakes with in relation to the source glaciers. Glacial meltwater leads into the lakes, therefore, there could be direct relationship established between the glacier dynamism and spatial extent of glacial lakes.

***Land Surface Temperature Estimation***

Extracting sub-datasets, layers 1 and 5 tiled days and night Land Surface temperature (LST) has been used. After re-projecting data sets to UTM 4N raster to ASCII function has been used for each image set to convert raster values into ASCII format. Day and night respective values individually iterated have been averaged to find out monthly LST for the concerned basin.

### *To Assess Potential Of Outburst Of Glacial Lakes*

Locations of lakes with relation to the parent glacier, area, depth, volume, morphological features, blockade type, etc. will be taken into consideration to classify the lakes in order of assess vulnerability of outburst. The high-resolution LISS III dataset will be visually interpreted for the classification of lakes in association with glacier inventory using the manual of (Babu Govindha Raj et al. 2013).

### *Volumetric Estimation of the Glacial Lakes*

Accurate estimation of volume for glacial lakes is imperative because this largely controls the magnitude of disaster level if discharge in case of an outburst in the future. Though glacial lake area can be calculated from the remotely sensed data sets, however; estimating accurate lake volume is not possible. Since there is no direct way to estimate the volume of lake water. Therefore, the Volume-Area-Depth empirical relationship will be used as has been done in the past in several studies. But, this can only give us a picture of an approximation of the selected lakes that are to be studied.

| PARAMETERS TO BE USED | FORMULAE | SOURCE |
|---|---|---|
| Area | $D_m$ (Mean Depth) = 55* (Area)^0.25<br>Volume = Area * $D_m$ | (Fujita et al., 2013) |
| Area | Volume = 0.104 * (Area)^1.42 | (Huggel, Kääb, Haeberli, Teysseire, & Paul, 2002) |
| Area | Volume= 0.191* (Area)^1.375 | (Bahr et al, 1997) |

**Table 1.1: Lake Area Calculation Formulae**

- ***Outburst Flood Potential Assessment:*** Hec-Geo Ras freely available software was used for 1D modelling. This gives a pictorial representation of the area to be inundated and flooded in case of outburst floods.

***Variables for Identifying the Causes and Impacts of GLOFs***

There are multitudes of criteria that increase the vulnerability and hazard potential of a glacial lake (McKillop & Clague, 2007) (ICIMOD, 2011). Some of the major recommended criteria for identification of the potential dangerous lakes are listed below:

1. Size and rapid areal increase of the glacial lake area.
2. Increase in depth and volume of a lake
3. Change in supra-glacial lakes at different times
4. Alignment of the lakes with respect to the source glacier
5. Moraine dam condition such as:
    - Freeboard characteristics
    - No drainage outflow or outlet for slow seepage of the lake water.
    - Height of the moraine
    - Gradient or steepness of the moraine dam.
    - Presence of ice core and / or permafrost within moraine materials.
    - Seepage through the moraine walls
    - Mass movement or ice avalanches on the inner or outer slope of moraine
6. Glacier associated parameters viz:
    - Source glacier condition
    - Presence of Hanging glacier
    - Extent of the parent glacier area
    - Swift recession of the glaciers
    - Debris covers on the lower glaciers
    - Slope of glacier tongue
    - Calving of ice from the glaciers
    - Blocks of ice falling and followed melting in the lakes
7. Geo-physical settings of surrounding such as:
    - Presence of mass movement sites near the lakes
    - Probability of snow avalanche in the vicinity of the lakes
    - Earthquake prone sites
    - Climatic conditions, particularly seasonal fluctuations.

***Flood Inundation Mapping***

Hec-Reas 1D modelling has been done for flood inundation mapping. Using empirical methods given by various scholars. Depth, volume, and peak discharge has been estimated for the selected lakes and eventually, hydro-dynamic Hec Geo Ras has been run to calculate the area under flood impact for further study.

***Probable Cost Analysis of the Losses in Downstream Areas***

For this purpose, quantitative values are taken into account. First, the value of individual properties was calculated. Later on, added together calculates a total probable loss value. The estimated losses were grouped into four categories: direct damage to real estate (land and houses); direct damage to agriculture (crops and livestock); direct damage to public infrastructure (roads, trails, bridges, schools, office buildings, temples, water mills, transmission lines, hydropower and others) and other indirect losses.

## 1.9 CHAPTERISATION SCHEME

- ***Chapter I. Introduction:*** This chapter will present a brief introduction of the glacial lakes, its different types, and how it culminates into GLOF phenomena. This chapter will give insight into the research problem; literature review; objectives of the study and its importance.
- ***Chapter II. Study Area:*** Geographical location and historical background of the study area; Physical and Socio-economic profile of the study area.
- ***Chapter III. Glacier and Glacial lake Inventory and its Dynamics in the region:*** This chapter will be about the inventory of Glacier and Glacial lakes in the Lahaul & Spiti basin in detail and the state of Himachal Pradesh in general along and its spatio-temporal changes. Picture of glacier dynamics quantified will be in this chapter with the help of techniques like change detection of Glacier snout position, glacial lakes and ELA. Glacial lake classification to be done will also be a part of this chapter.
- ***Chapter IV: Study of glacial lake environments of potentially dangerous glacial lakes (PDGLs).*** This chapter is about the study of marked Spatio-temporal changes of selected glacial lakes through different time scales and

seasons. LST has also been studied to understand the impact of temperature changes on the dynamics of glacial lakes.

- ***Chapter V: Flood inundation mapping:*** This chapter deals with the impact area under potential impact in case of glacial lake outburst floods. Calculating depth, volume and peak discharge, overall area under the impact of GLOF has been used for the year 2020. At the same using present values, future volume and peak discharge have been estimated for a period 2040 and then the area under flood inundation has been mapped for Sissu and Samudra Tapu lakes.
- ***Chapter VI:*** **Socio-economic cost estimation:** This chapter is about the probable monetary value of losses in the face of breaches and inundations downstream for the Sissu and the Samudra Tapu glacial lakes.
- ***Chapter VI. Summary and Conclusion:*** The last section summarizes the conclusions and the contribution of all the chapters of the entire research work. The research gap and its future scope will also be highlighted in this concluded part.

# CHAPTER 2

# GEO-PHYSICAL SETTING OF THE STUDY AREA

## 2.1 INTRODUCTION

Lahaul and Spiti, the largest administrative district of Himachal Pradesh is comprised of the Lahaul and Spiti valley as its geographic entity. The district is located in the north and north-east part of Himachal Pradesh. It is bordered by Tibet on the east, and to the north by Ladakh. The west and south are bordered with Chamba, Kangra and Kullu districts and on the south east by Kinnaur district. It is located between the latitudes of 310 44' 57" and 320 59' 57" in north and between 760 46' 29" and 780 41' 34" east longitudes. Lahaul and Spiti district has an area of 13,841 kmˆ2 constituting 24.85 percent of the total geographical area of the state. The two valleys of Lahaul and Spiti are linked together by the Kunzam pass (4,520 meters) .Rohtang pass provides an access to Lahaul.

Lahaul and Spiti remained a part of two Kingdoms viz.: Ladakh and Kulu. Prior to the seventeenth century, it was a part of Ladakh kingdom administratively but later on after the disintegration of Ladakh as a kingdom, it fell into the hands of Kulu, ruled by Maharaja Ranjeet Singh. It continued to have a submissive identity for a very long time until the rise of the conscious minds of the locals to give it a new identity. Finally in 1941, a separate sub-tehsil comprising of Lahaul and Spiti was formed. In 1960 it was given the status of the statehood with Kaza as administrative headquarter of Spiti and Keylong for Lahaul subsequently during the British part of Kangra district back then.

It is the least populated district flanked by mountains from all sides devoid of towns and cities. There are two administrative divisions as tehsils viz. Keylong and Kaza, there is 1 sub-tehsils Udaipur in Keylong. It is a district with an immense amount of natural beauty with prominent features characterized by lofty mountain ranges incised by deeply dissected valleys carved out in slopes of various descriptions. It is a cold desert with an abundance of glaciers and snow. Being a part of different agro-climatic geography, it holds immense potential for off-season vegetables and fruits, along with floriculture.

For all purposes, water comes from the glaciers and snow-melt, be it for domestic use or agriculture. Therefore 100% dependence on the glaciers and existing climate.

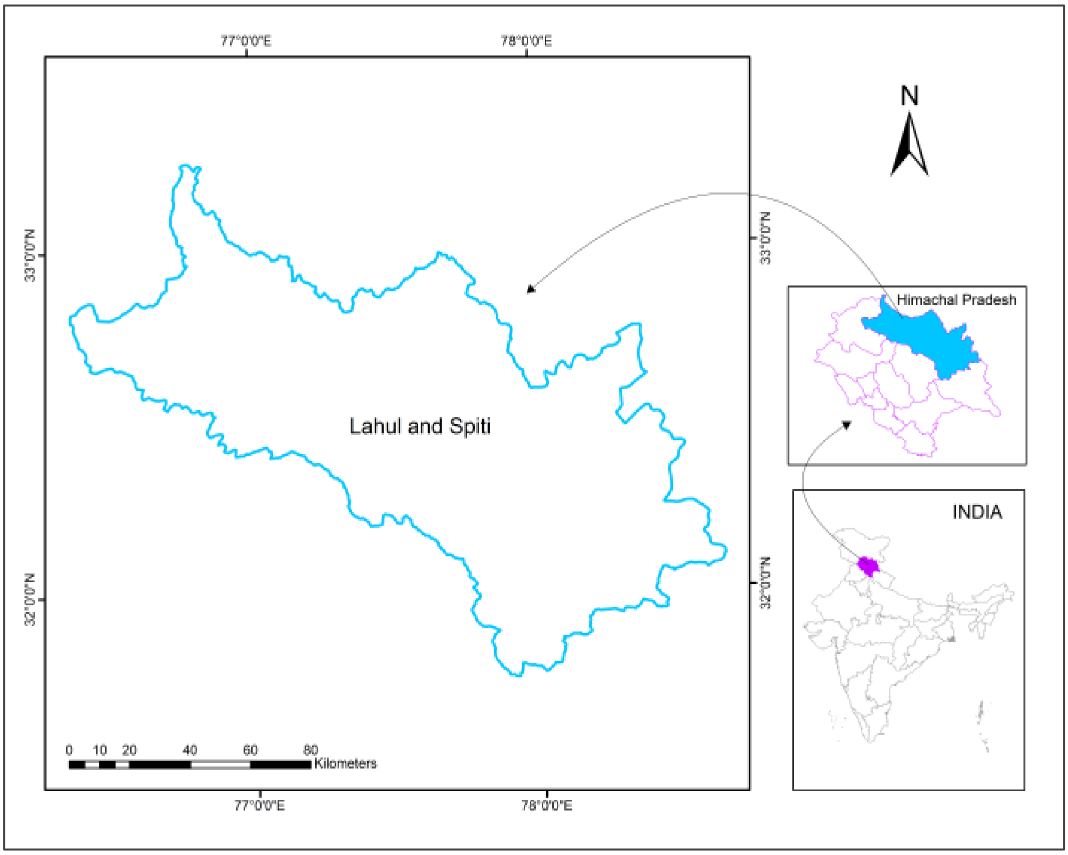



**Fig. 2.1 Study Area: Lahaul & Spiti**

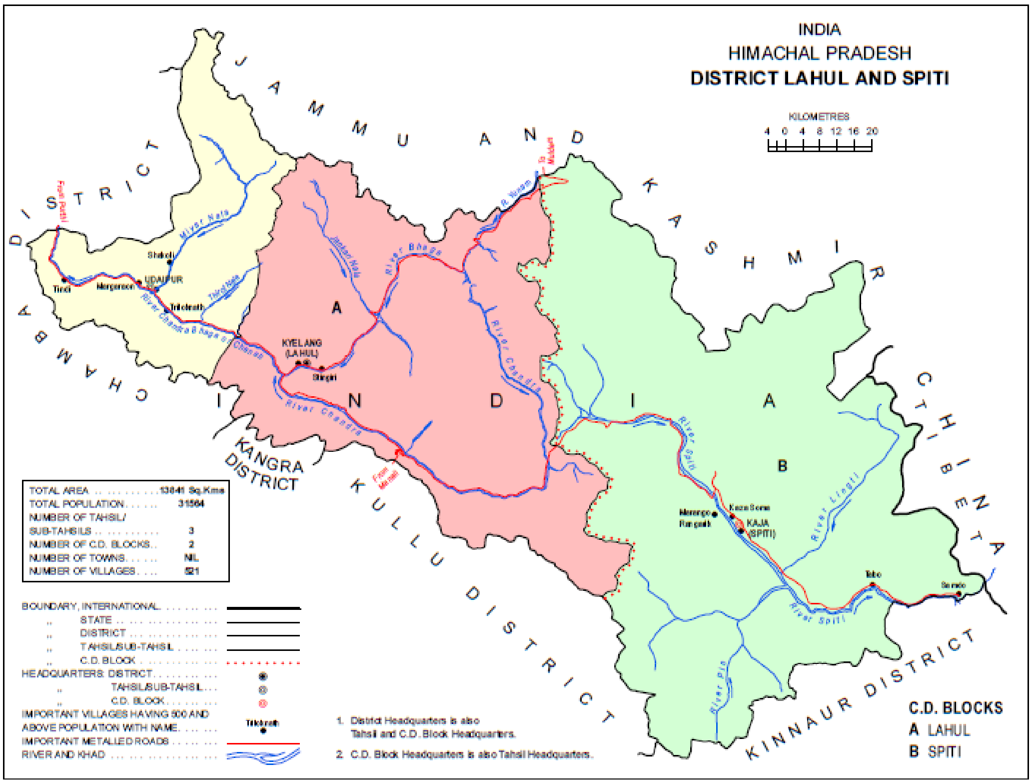



**Fig.2.2 Administrative Units of Lahaul and Spiti with the Refrence to Neighbouring Regions.**

Source: District Census Handbook, 2011

## 2.2 PHYSIOGRAPHIC SETTING

Lahaul and Spiti through part of one district only but are contrastingly different units in terms of physiography as well as culture. The difference in the underlying lithology and the varying interplay of various geomorphic processes has resulted in large intra-regional physiographic variations. Lahaul in general has bare and rough terrain and steep slopes except in the western part where one encounters pine vegetation. The region has two prominent physiographic units:

- The mountain ranges; and
- The river valleys

## 2.3 THE MOUNTAIN RANGES

The Himalayas is a series of several parallel and converging ranges instead of a single continuous range and intersected by numerous valleys. The same is exhibited in the small region of the Lahaul by Lesser Himalayas in the north-west to south-east direction and the Greater Himalayas in the north-east. The Pir Panjal range of the Lesser Himalayas and Zanskar range of the Greater Himalayas give striking intra-physiographic variations.

The Pir Panjal range has an average height between 3500 to 5000 meters. However, many peaks exceeding 6000 meters are Dara Goh, Khodo Goh, and Makar-Beh. The wall created by this range obstructs the monsoon and reduces the amount of rainfall and vegetation in this region. The continuous wall of the Pir Panjal range restricts the accessibility only through the Rohtang Pass (3955 meters).Geologically, the middle Himalayas of this part is composed of a zone of highly compressed and altered rocks of various ages(District Gazetter,2011).

The Greater Himalayan range, in the north-east of this region, consisting of intricately ramifying glaciated ranges of crystalline rocks is an important range in the region. The average height of this range is 5000 meters which finally merges into the Pir Panjal range in the eastern part. Some fringes of this range run from north to south. The Greater Himalayan part is constituted of more glaciers as compared to the Pir

Panjal. However, the Pir Panjal contains one of the largest glaciers, i.e. Bara Shigri right close to its merger with the Greater Himalayan range at Kunlun Pass.

**Plate 1: Landscape of the Great and Middle Himalaya (*Pir Panjal range in the background*). The configuration of ranges and altitude have given rise to glacier formation and atypical climate.**

**Plate 2: Desolate landscape in the rain-shadow zone of the Zaskar Range beyond Baralacha. Frost Shattering is the order of the day in this Himalayan tract within Lahaul.**

## 2.4 PHYSIOGRAPHIC DIVISIONS

The Lahaul and Spiti region, broadly mountainous terrain can be divided into five valleys with distinct characteristics with the adjoining units. They are:

1) The Chandra Valley
2) The Bhaga Valley
3) The Patan Valley
4) The Chenab Valley and lastly,
5) The Central Triangular Mass.

### 2.4.1 *The Chandra Valley*

The Chandra Valley begins from the south-eastern part of the Baralacha Pass (4880 meters). A larger part of the valley is uninhabited and the slopes are characteristically stony and bare. This is the area of extreme climate and is generally influenced by the climate of Kullu in the monsoon season. The total length of this river valley is about 112 kilometeres.

The Greater Himalaya merges into the Pir Panjal in the east of the valley. Most of the tributaries of river Chandra in this part are fed by the huge glaciers of the Samudara, the Bara Shigri, and the Dhaka and, others. But the valley becomes less oppressive and green below Gramphu. The valley on the right bank of the river is wider being high terrace, consequently, human settlements occur in the area. The fluvial and glacio-fluvial deposits are encountered all over the valley. The Bara Shigri glacier on the right bank of the river Chandra which descends to the river bed is the largest glacier in Lahaul with an approximate area of 126.45 km2.

The altitude of the Chandra Valley varies from 3007 meters at the confluence to 4877 meters at the source. The natural vegetation starts from Sissu onwards in the form of deodar, blue pine and birch. Human activities are mainly concentrating on the right bank. The left bank of the river Chandra is generally very steep and inhospitable except in three small villages which are situated on alluvial fans and huge talus-cones. The large lake Chandra Tal, which has a length of one kilometre and is half a kilometre in width lies between a low ridge and the main Kunzum range at an altitude of 4419 meters. Most of the talus cones and the glacio-fluvial terraces in the shape of meadows are utilized by the shepherds in the summer season in the higher reaches.

**Plate 3 Meadows in the Chandra valley region used by the Shepherds during summers for cattle grazing.**

## 2.*4.2: The Bhaga Valley*

The Bhaga valley starts from the source of the Bhaga River in the south-western part of the Baralacha pass at an altitude of 4800 meters. This valley has rocky rugged and terrain with barren rocky slopes. The general aspect of the valley is from south-west to north-west while the average height is about 5000 meters.

The total length of the valley is about 65 meters. The river Bhaga in the valley is entirely fed by the small rivulets glacially originated. The important tributaries are Milang nallah and Biling nallah originating from Mulkila glaciers and Gangstangand Zankar Chhu glaciers, respectively.

**Plate 4: Narrow river valley of Billing (Gangstang) Nalah. Downstream are the villages of Billing and Keylong.**

### *2.4.3. The Patan Valley*

The Patan Valley encompasses the area between Tandi (confluence of river Chandra and Bhaga) to Thirot. This valley is characteristically different from the others in terms of physical parameters as well as population parameter. The valley has width of about 1.5 to 2 kilometres and an average altitude of 4400 meters.

The valley is less rugged and all of the right bank tributaries originate from the Gangstang glacier. This valley has settlements of large size with a relatively high concentration of population. The valley is quite fertile where most of the human habitation is situated on river terraces, alluvial fans and talus cones. On the other hand left bank constituted by the Pir Panjal range is very steep with only few villages.

### 2.4.4. *The Chenab Valley*

The Chenab valley is between Thirot and Sach Pass with an area of approximately 1912 square kilometres. Most of this area is left uninhibited with vast tract of untapped forest resources and settlement is seen on the gentle slopes where there is an availability of ample irrigation facilities. The valley has an average altitude quite less as compared to other valleys but has extensive width of about 2 to 3 kilometers.

**Plate 5: The Miyar nallah flowing in the region is the major tributary of river Chenab passing through a deep gorge to meet river Chenab at Udaipur.**

### 2.4.5. *The Central Triangular Mass*

The centre of Lahaul region is occupied by a triangular mass enclosed by Chandra and Bhaga River. On the top are lateral spurs with intervening valleys filled with glaciers and uninterrupted snow. Glaciers from this particular region are the source of perennial water to both the Chandra and Bhaga rivers, biggest one being the Samudara glacier.

The Bara Lacha Pass is an important feature of this region which is about 8 km long. From this pass originates Bhaga River in the north-west, Yunan in the north and Chandra in the south-west. A vast land piece named Lingti maidan is there to the north of Baralacha pass which is not cultivated and is uninhibited as well owing to its harsh climatic conditions but still is being used by Gaddis in summers as pastures.

## *2.4.6. Processes and Resulting Land Forms*

In the entire region multitude of different forces have acted either individually or collectively to give shape to the present day landforms but these natural forces are dominated by glacial actions over the years.

***Erosional Features:***

Extensive glacial processes have resulted in the formation of the large number of U-shaped valleys in the entire region while entire valleys viz. Chandra and Bhaga and some tributaries of Chenab valley can be ascribed as trough valleys due to variable resistance offered by the underlying geological structure. The central triangular mass between Chandra and the Bhaga has a number of Cirques that are the source of glaciers, along with large valley glaciers.

***Depositional Features:***

Moraines, till and erratics are the depositional features of glaciers in the region. Within moraines, recessional moraines, lateral moraines, medial moraines are very much visible.

***Glacio-fluvial Processes and the Features:***

Landforms formed due to the combined action of glaciers and streams originating from glaciers are termed as glacio-fluvial landforms and that depends on the underlying region and climatic conditions therein. Outwash Plains, eskers, kames, terraces, and kettle hole, etc. are formed in Lahaul region. Glacio-fluvial terraces exist on many tributaries of the river Chandra-Bhaga and Chenab that serve the purpose of pastures for grazing. The outwash plain in the form of valley trains can be seen in Miyar and Thirot Nallahs.

***Fluvial Processes and Landforms:***

A trio of activities viz erosion, transportation and deposition are being performed by rivers in Lahaul. The shape of the valley is influenced by the climate, rock type, available relief and geological structures associated with the nature of slope but most importantly the stage and intensity of the fluvial process. For instance V-shaped valley here is the result of streams in youth, whereas a wide broad flat bottomed valley represents old stage of the river.

***Depositional Features:***

The most astonishing feature of fluvial deposits in Lahaul is the alluvial fans but they have been undergoing under human interventions. Alluvial fans are formed at foot of steep slope areas where it gives way to gentle slope. Fertile cultivable terraces are another feature of fluvial deposits. These terraces are very well utilized by humans.

Tandi, Tholong, Lote, Kirting, Sansha are the major settlements on terraces only. Rounded pebbles, stones and sand can be encountered on these terraces.

Erosional Features'-shaped valleys an erosional landform is a characteristic feature of the youthful stage of the river. The main valleys of Chandra, Bhaga and combined exhibit somewhat broad and flat bottom resembling modified U-shaped valley due to the past glacial influence while tributaries depict V-shaped. The picture shows the V-shaped valley of Milang Nallah at Darcha. In the foreground is the braided channel of Bhaga; where 3 rivers viz the Bhaga, the Milang and the Zankar Chhu meet and have deposited large transported material that makes it flattened and braided for a short distance. The eroded terraces are difficult to identify for being filled by the weathered deposits. The pot-holes are prevalent all along the course of river Chandra as a result of scouring and grinding.

***Weathering:***

Weathering is an important phenomenon that shapes and reshapes the landscape. Out of all weathering agents, temperature changes, frost action and changes in crystal growth and pressure release etc. are dominant in Lahaul. Weathering distingerates rocks in a freeze and thaw action in this region that happens due to crystallisation of water into ice under cold climatic conditions. Later on these weathered disintegration rock fragments come down under the impact of gravity, accumulate and undergo further disintegration and shatter. The resulting soils or regolith slowly move down which is known as soils creep. The soil resulting in talus-cones in the region is in abundance.

## 2.5 GEOLOGY AND LITHOLOGY

Geologically the district has basal rocks of the Pre-Cambrian to the Cretaceous era. Thus it has a complete sequential evolutional evidences.

Proterozoic: This is the most ancient geological and lithological unit found in Spiti Valley constituting the Vaikrita group.

Palaeozoic: This system forms a curved part between Chandra River and the boundary of the district in the south-east. This system further has its extent in the north-wets regions of the Lahaul valley. These formations have varied lithological structures in the upper, middle and lower stages where the lower part is highly folded. These formations are fossilified. (H.P.District Gazetteer, 1975)

Mesozoic: These are the most complete and comprehensive geological unit witnessed in the district.

## 2.6 SOIL

The Soil type of any region is a function of its geological structure. Therefore, depending on the parent geology soil type varies in different regions with physical and chemical properties. The Lahaul region has predominance of silty-clay loam whereas the Spiti region has a predominance of silty loam. Brown coloured soil is found in the lower altitudes of Lahaul valley which is characterized by fine texture. It has its roots in mica-schist. These types of soil are abundant in potash but lack lime, magnesia, nitrogen and phosphorous making it less fertile.

Overall in general the soil is alkaline in nature and poor in organic matter. There is good amount of calcium because of abundance of shale, slate and phyllites which get easily weathered and eroded for being soft in nature. These are the most spread out soil type supporting good amount of vegetation as well. Absence of substantial leaching of minerals from the soil in most of the parts of the region particularly in Spiti valley and dry alpine areas of Lahaul, adds minerals continuously in the soil, effecting soil pH which tends to increase. The most of the soil is transported by the rivers, avalanches and wind effects. Soluble salts in the soil are present in considerable amounts.

## 2.7 CLIMATE

Lahaul region undergoes extremes of climate all through the year in terms of temperature, rainfall and snowfall. This is primarily due to longitudinal alignment of the Pir Panjal ranges and high altitudinal feature. The winter season in the region lasts from the end of November to March followed by Spring that goes up to May and the summer season lasts from June to September while October and part of November marks the transitional climatic conditions. The climate of the district is characterized by general dryness throughout the year as the district lies between the eastern or main the Himalayas on the north and the mid Himalayas on the south. The mean altitude of the district is above 2,700 metres with major part of the region has an altitude of 4,000 metres to 6,000 metres. Some of the peaks are beyond 6,400 metres. The seasons are more like the temperate zone. The winter season start from about the middle of November to March followed by the spring which last up to the end of May. The next four months may be termed as summer season. The Spiti region of the district is relatively harsher than the Lahul, terms of terrain, climate and habitation. From June to mid-September, the day temperature increases making summers warm but the nights colder. Snowfall starts from October and lasts till December. These months experience severe cold with frequent snowfall. Chandra Bhaga valley has temperate climatic conditions in summer and semi arctic in winter. Though snow fall starts in October but it doesn’t get accumulated since the ablation process continues till December. The monsoon hardly penetrates into the district as gets obstructed by the mid Himalayan mountain ranges Spiti region of the district is also typical mountainous cold desert and rains reach there in the form of drizzles only. Lahaul and Spiti receives the least amount of precipitation within the state. Maximum precipitation is in the form of snowfall from mid-latitude westerlies and in summer from south-west monsoon. The highest average annual rainfall was recorded for the district in the year 2005 i.e. 795.4mm as well as for the State was 1189.6 mm whereas the highest difference of the same was recorded in the year 2008 of 729.4 mm

| S.No. | Year | Average Annual Rainfall (in mm) | |
|---|---|---|---|
| | | Himachal Pradesh | Lahaul and Spiti |
| 1 | 2004 | 1000.70 | 348.20 |
| 2 | 2005 | 1189.60 | 795.40 |
| 3 | 2006 | 1102.50 | 490.80 |
| 4 | 2007 | 1000.50 | 336.00 |
| 5 | 2008 | 1141.00 | 411.60 |
| **6** | **2009** | **907.90** | **706.30** |

**Table 2.1 Average Annual Rainfall in Himachal Pradesh and Lahaul & Spit**

**Source: India Meterological Department**

Within the Lahaul valley itself data recorded at two stations viz. Keylong and Udaipur shows the distributional pattern of annual precipitation viz rainfall and temperature in the graphs below:

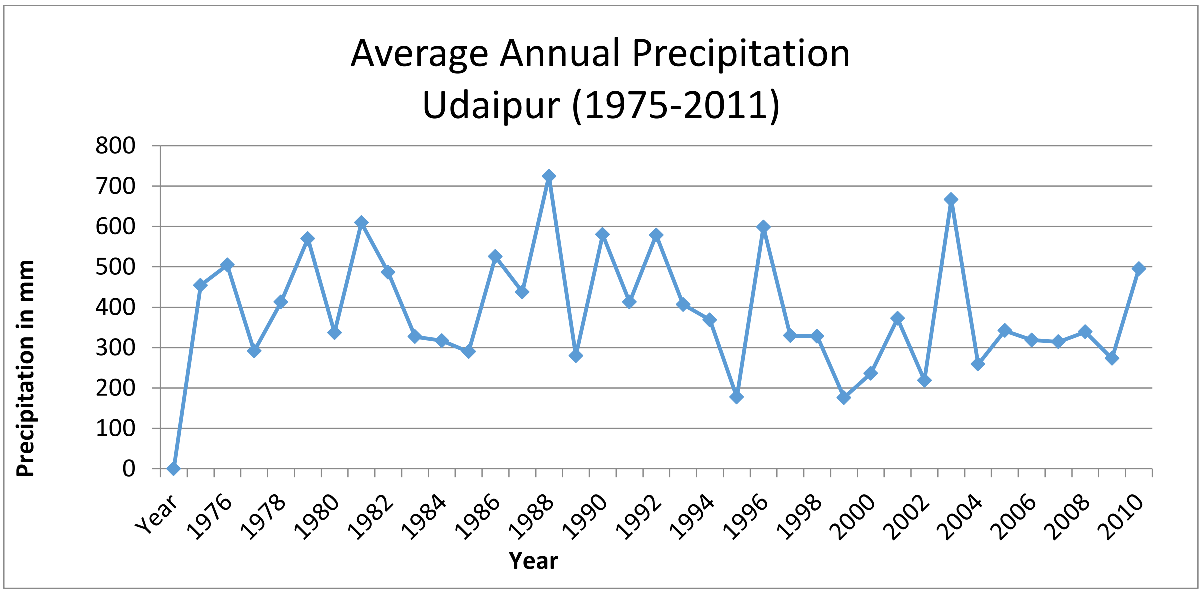



**Fig 2.3 Distribution of Average Annual Precipitation in Udaipur.**

The maximum and minimum temperature in 2010 at nearest selected centre Keylong reveals that the maximum temperature ranges from 23.9 ºC in August to 0.8 ºC in the month of January, whereas the minimum temperature ranges reduces 14.9 ºC in August to -10.3 ºC in the month of January. The warmest

Months are July and August. The air is generally dry over the district during summer and transition seasons. It is also dry in winter except during the rains or snowfall.

| Month | Maximum Temperature (in degree Celsius) | Minimum Temperature(in degree Celsius) |
|---|---|---|
| January | 0.8 | -10.3 |
| February | 2 | -9 |
| March | 8.1 | -3.6 |
| April | 14.8 | 3.4 |
| May | 18.4 | 6.2 |
| June | 20.5 | 8.1 |
| July | 23.8 | 12.9 |
| August | 23.9 | 14.9 |
| September | 17.6 | 10.6 |
| October | 14.8 | 3.7 |
| November | 9.4 | -0.6 |
| December | 5.9 | -4.9 |

**Table 2.2. Monthly Maximum and Minimum Temperature data recorded at Keylong district Lahaul & Spiti 2010**.

**(Source: IMD, 2010)**

In terms of rainfall and snowfall, there is stark variability and difference within different seasons temporally. There has been a gradual decrease in the amount rainfall till 2017 with marked heavy rainfall in the year 1995 then in the year 2011.Eventually there is continuous decrease in rainfall pattern(chart).In terms of snowfall, barring exceptionally heavy snowfall in the year 2001;there is again a continuous decline till 2017(chart2.1)

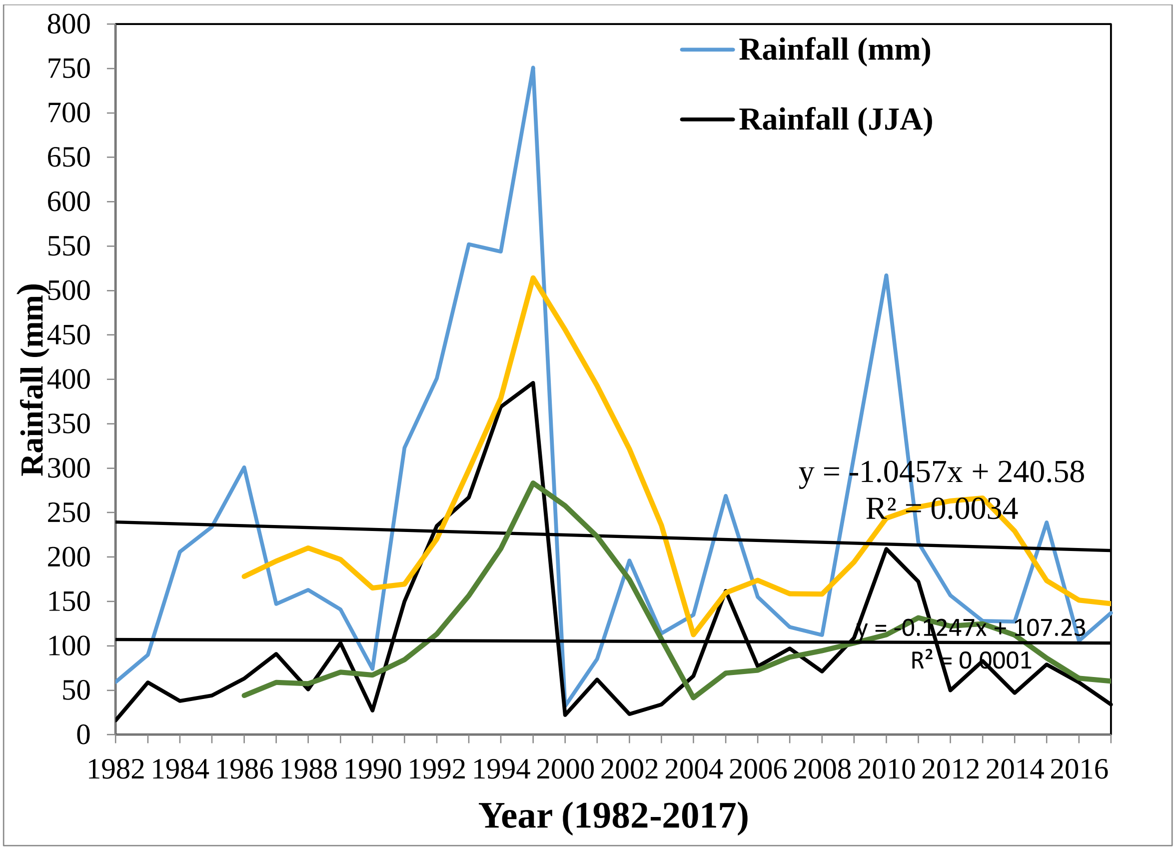



**Fig.2.4 Rainfall distribution at Keylong from 1982-2017**

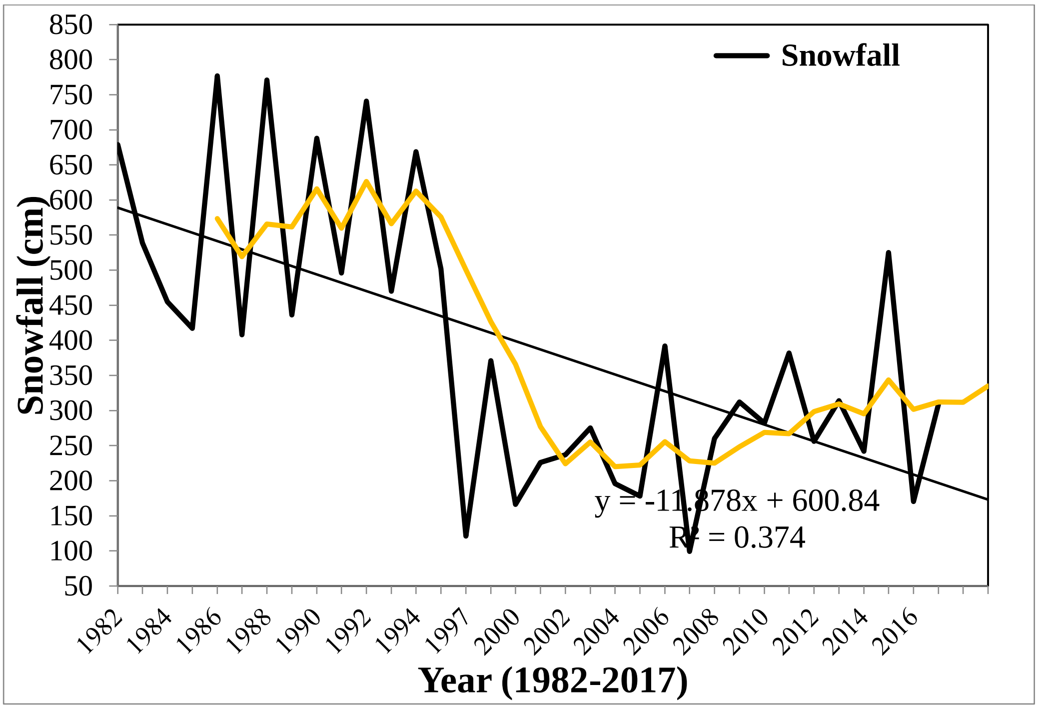



**Fig. 2.5 Snowfall distribution at Keylong from 1982-2017**

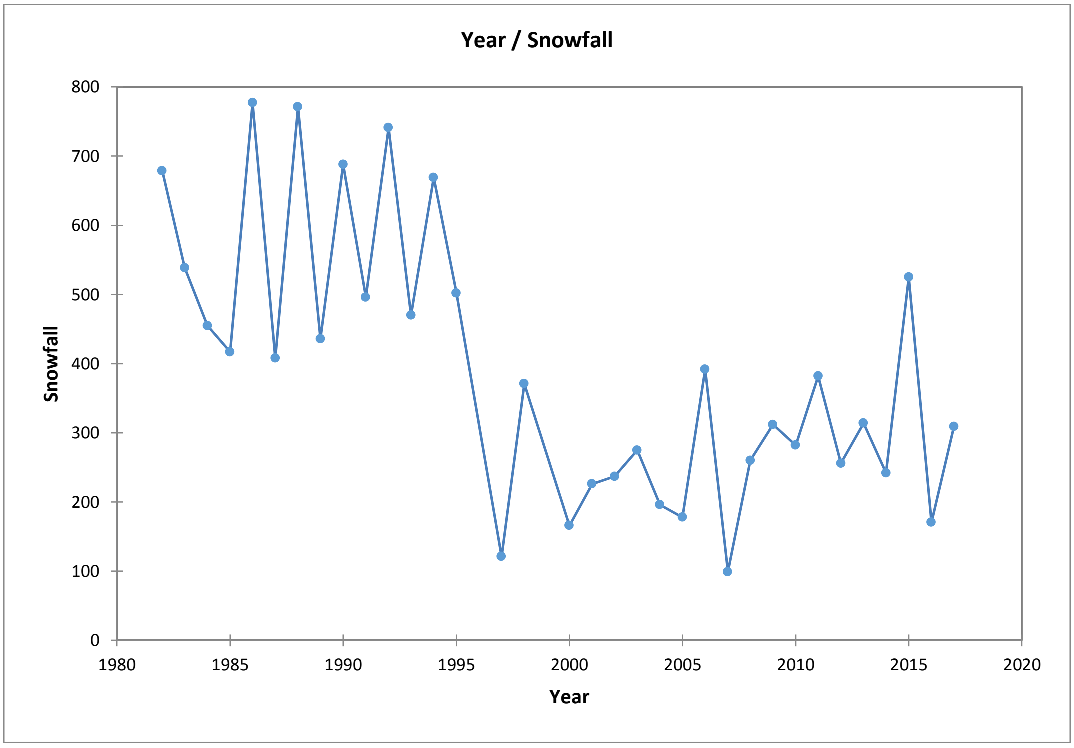



**Fig 2.6 Yearly Snowfall Distribution at Keylong.**

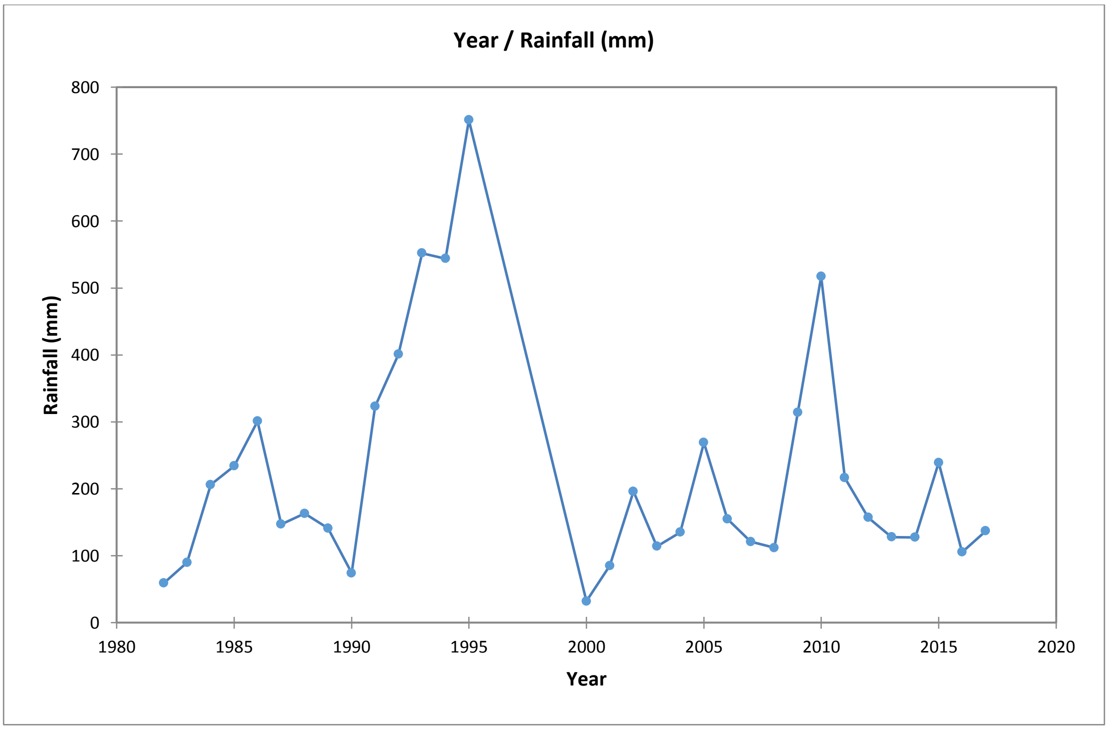



**Fig 2.7 Annual Rainfall distribution at Keylong.**

## 2.8 VEGETATION

The vegetation in the entire Lahaul-Spiti region is very sparse and unique. It supports the very scanty and highly diverse types of plants. The major part of the district has dry temperate to the dry alpine type vegetation. The dry type of vegetation is due to scanty or absence of rainfall, great variation in temperature, ultraviolet radiations, heavy snowfall, ground topography, soil texture, low moisture, low fertility, high speed winds, etc. Lahaul and Spiti valley differ greatly in their vegetation cover. The topography is varied. The Lahaul is much green than Spiti. In Lahaul valley, the vegetation between Udaipur – Keylong to Darcha is of dry temperate to alpine type. Some parts of Pattan Valley between Thirot (3,000 m) to Purthi (2,400 m) adjoining the Pangi area of Chamba district the vegetation is of dry temperate to moist temperate type. The Trilokinath area along the river Chandrabhaga supports pure patches of moist temperate vegetation. On the other hand the vegetative cover of the Spiti valley is comparatively poor to that of the Lahaul valley. It is very scanty owing to the prevailing severe cold and dry climate. The majority of plants growing in the area have cushion, clump or mat-forming habit. The vegetation of the Spiti valley varies from semi-desert to desert, depending upon the prevailing bio-climate. For example, the major part of the area in and around the Kaza is desert -like and plants survive along the hill streams and the river beds. The plants of Lahaul-Spiti depict a number of ecological, morphological and physiological adaptations which help them adjust to the harsh climatic condition of these regions. The majority of the plants tend to become thick wooly, bushy, hardy and spiny with deep and long roots with small leaves. The vegetation of the regions can be divided into temperate type (2,400m – 3,500m) and alpine type (above 3,500m). The remarkable feature of the vegetation is that south and eastward slopes are devoid of vegetation while north and west have presence of numerous plants. The flora is of the steppe type and is rich at lower elevations but becomes poorer upwards.

- **Temperate zone (2,400m – 3,500m)**

The temperate zone in the Lahaul area is characterized by the presence of nearly all the woody shrubs and trees. These are both indigenous and exotic which are of special significance and importance to the local population for their food, fodder and fuel. It includes Apricot,Blue pine Birch Deodar Juniperus  Poplars,Spruce, Walnut,Willows.

The temperate vegetation cover is scanty in the Spiti area and trees are almost absent except poplar and willows planted around human inhabitations.

- **Alpine Zone (above 3,500m)**

The zone above the tree line is generally considered as Alpine zone. In the alpine zone, where the ground is covered with snow for more than six months in a year, supports very scant vegetation that can be subdivided into three parts viz. Alpine forests , Alpine scrubs and , Alpine meadows.

The NDVI map prepared using satellite data shows the maximum availability of vegetation only in a narrow patch of belt in linear for towards the southern and north-western part of Lahaul and Spiti while the upper part of Lahaul and Spiti is a barren deserted place devoid of vegetation completely.

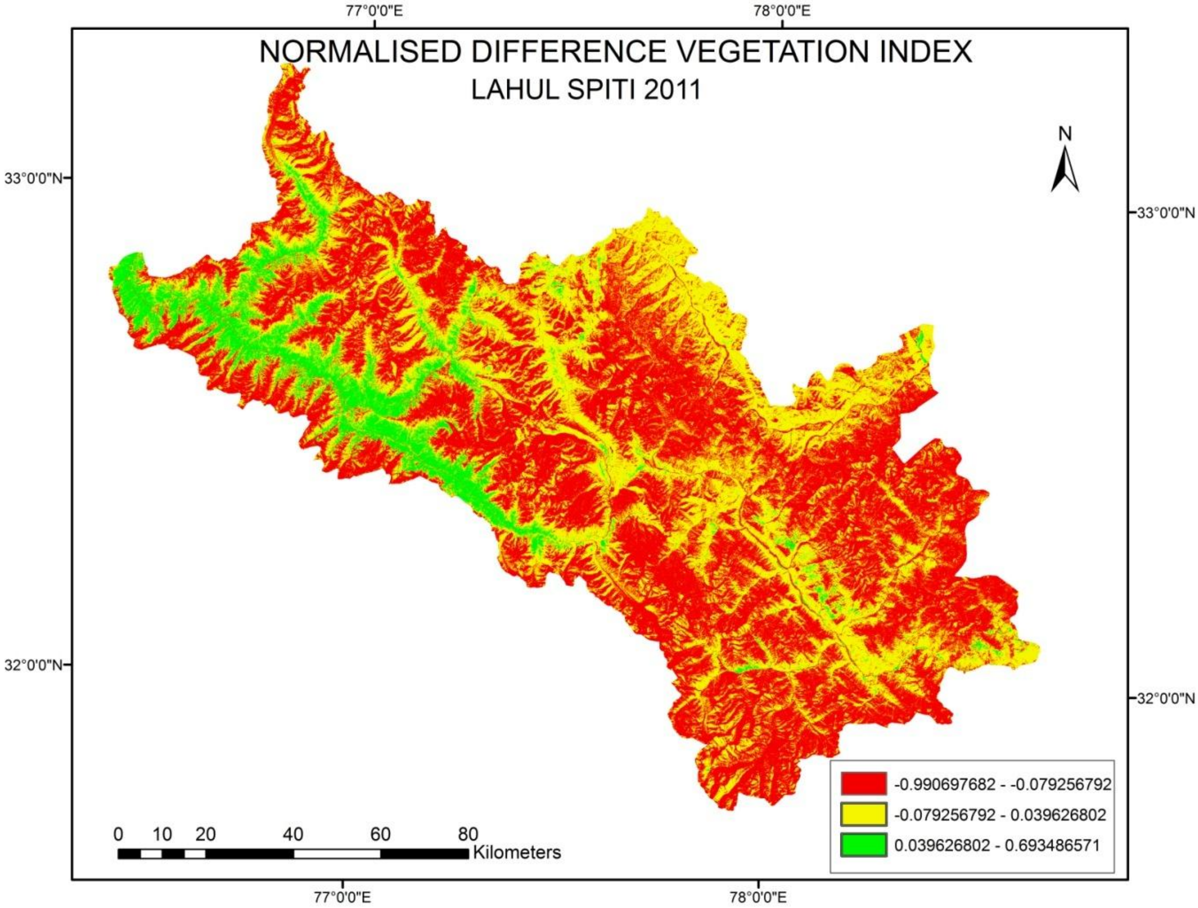



**Fig 2.8: Normalised Difference Vegetation Map of Lahaul and Spiti**

## 2.9 SOCIAL PROFILE

Lahul & Spiti district is the largest district of the state in terms of its area with an area of 13,841square kilometer forming 24.9 percent of the total area of the state. But has the least population of 31,564 thousand only as per 2011 Census with 16,588 males and 14,976 females. The population of the district is merely 0.5 percent out of 68,64,602 population of the state. Lahul & Spiti district has total 521 villages, out of which 241 villages are uninhabited. This entire population of the district is distributed in 280 inhabited villages. There are 236 villages which consists population less than 200 and 187 villages having population less than 100(District Census Handbook, 2011 Part 12-A).These villages are mostly scattered in valley of Chandra-Bhaga river and its tributaries in Lahul tahsil and Udaipur sub-tahsil and valleys of Spiti, Pin and Lingnti rivers in Spiti tahsil. Higher altitude areas as these remain under snow cover and unhabitated. The district has no urban area and the rural population is distributed in three sub-districts/sub-tahsil. Lahul tahsil has a population of 10,218 comprising 5,418 males and 4,803 females while the Udaipur sub-tahsil contains 8,889 persons consisting 4,482 males and 4,407 females while Spiti tahsil is inhabited by 12,457 persons with 6,691 males and 5,766 females. The total number of households in the district comes to 6,674 and average size of households works out to 4 persons per household according to 2011 Census. These households are distributed as (1,869) in Udaipur sub-tahsil, Lahul (2,222) and Spiti (2,583) tahsil.

The district registered a very low growth rate during 1901 to 1951, it fluctuated between 4.8 to 5.1 percent, except 1921 when its population declined by 1.1 per cent. In 1961 Census, district recorded very high growth rate of 54.4 per cent and which is due to the in-migration of workers engaged in different developmental projects especially in road construction work. During the decades of 1961-71 and 1971-81 the growth rates were 16.4 and 16.4 per cent, respectively. During decade of 1981-91, the population of the district declined by 2.5 per cent, but in the subsequent decade 1991-2001 population inclined by 6.2 per cent. Population growth in the district is an outcome of large out-migration, due to lack of employment opportunities, specialized medical facilities and for better education.

- **Density of Population:** This district has unevenly distributed low density of population. The average density of population is only 2 persons per km2 against the state average of 123 persons per km2 in Census 2011.The physical and climatic conditions are very harsh and not suitable for human habitation in this district resulting in low population and slow population growth.

- **Sex Ratio:** Sex ratio for the district has been worked out as 903 against the state average of 972 in census 2011. The Sex-ratio from 1901-2011 has been discussed in Table 4.In Census 2011 at tahsil level, it varies between 983 in Udaipur sub-tahsil and 887 in Spiti tahsil while Lahul tahsil has lowest sex ratio of 862. Among the child population in age group 0-6, it comes to 1033 females per 1,000 male's which is above than parity line. Moreover sex ratio among the tribal population is very high in the district which is 1,017 and clearly indicates that total sex ratio is greatly influenced by the workers migrated from other areas who usually come without their family for earning their livelihood. Sex ratio among the Scheduled Castes population is 937 in the district.

- **Work Participation Rate**: Out of the total population of district, 19,295 have been categorized as total workers encompassing main and marginal workers constituting 61.1 per cent of the total population. 48.1% of population is recorded as main workers and 13.0% as marginal workers. At tahsil level, the highest percentage of total workers has been recorded in Lahul tahsil (72.5) and is followed by Spiti (57.1) tahsil. Udaipur sub-tahsil has lowest proportion of 53.8 per cent. The male work participation rate, the proportion of total male workers comes to 64.9 per cent of the total male population while female participation rate works out to 57.0 per cent in the district. Male marginal workers constitute only 18.9 per cent and the proportion of female marginal workers is 13.8 per cent. At sub-districts level percentage of male workers is higher than female workers in all subdistricts/sub-tahsil.

- **Scheduled Castes and Scheduled Tribes population, 2011:**

The Scheduled Castes population i.e. 2,235 that is 7.1 per cent of the total population of the district. Sex-ratio among the Scheduled Castes is 937. The literacy rate is 79.9 per cent among the Scheduled Caste. The Males and Females literacy rate in

Scheduled Castes to that of total population are 90.0 per cent & 69.1 per cent, respectively. Scheduled Tribes population is 25,707 that is 81.4 per cent of the total population of the district. It is predominantly a a tribal district. The sex-ratio among the Scheduled Tribes population is 1,017. The sex-ratio is much higher in Scheduled Tribes than the Scheduled Castes. The literacy rate is 76.9 per cent among Scheduled Tribes population in the district. The males and females literacy rate in Scheduled Tribes to population are 86.9 per cent & 67.1 per cent, respectively.

| Year | Himachal Pradesh | | | Lahaul and Spiti | | |
|---|---|---|---|---|---|---|
| | Total | Rural | Urban | Total | Rural | Urban |
| 1901 | 884 | 899 | 600 | 992 | 992 | Nil |
| 1911 | 889 | 905 | 499 | 990 | 990 | - |
| 1921 | 890 | 908 | 490 | 993 | 993 | - |
| 1931 | 897 | 915 | 521 | 989 | 989 | - |
| 1941 | 890 | 907 | 542 | 920 | 920 | - |
| 1951 | 912 | 932 | 664 | 933 | 933 | - |
| 1961 | 938 | 961 | 650 | 786 | 786 | - |
| 1971 | 958 | 976 | 749 | 818 | 818 | - |
| 1981 | 973 | 989 | 795 | 767 | 767 | - |
| 1991 | 976 | 990 | 831 | 817 | 817 | - |
| 2001 | 968 | 989 | 795 | 80 | 80 | - |
| 2011 | 972 | 986 | 853 | 903 | 903 | - |

**Table 2.3: Decadal Rural-Urban Population Distribution of the State and the district of Lahaul& Spiti**

| No. | Area | Total Population | Total S.C Population | Total S.T Population | % of S.C Population | % of S.T Population |
|---|---|---|---|---|---|---|
| 1 | Lahaul | 19107 | 1699 | 15163 | 8.89 | 79.36 |
| 2 | Spiti | 12457 | 536 | 10544 | 4.30 | 84.64 |
| | Total | 31564 | 2235 | 25707 | 7.09 | 81.44 |

**Table 2.4 Distribution of Scheduled Castes and Scheduled Tribes population in Lahaul and Spiti**

The district has total rural jurisdiction which contains 81.44 per cent of total Scheduled Tribes population and 7.08 per cent belongs to Scheduled Castes. Lahaul 79.36 per cent of Scheduled Tribe population and 8.89 per cent Scheduled Caste population, while the Spiti region has 81.44 per cent Scheduled Tribes and 4.30 per cent Scheduled Castes population.

| No. | Area | Literacy Rate in % | | | Literacy Gap |
|---|---|---|---|---|---|
| | | Total | Male | Female | |
| 1 | Lahaul | 74.79 | 84.59 | 65.50 | 20.09 |
| 2 | Spiti | 79.76 | 87.37 | 70.74 | 16.63 |
| 3 | Total | 76.81 | 85.69 | 66.84 | 18.85 |

**Table 2.5: Literacy Rate by Sex in Lahaul and Spiti 2011**

## 2.10 CONCLUSION

Himachal Pradesh a Himalayan state with rugged topography is abundantly rich with glaciers and snow. Physiographically, it depicts prominent differences among the districts in terms of rainfall, temperature, snowfall, vegetation and soil characteristics. Socially and culturally, the region is not that dissimilar. Majority of the population is agrarian for the means of sustenance. Agricultural and important predominant agricultural activity is dependent of Kuhls that is glacial melt waters. Since glaciers are an important source of irrigation, it is imperative to study in depth the dynamism and extent of glaciers within the state.

# CHAPTER 3

# GLACIER AND GLACIAL LAKES INVENTORY

## 3.1 INTRODUCTION

Ice and snow are the biggest reservoir of freshwater outside the realm of oceans which is distributed in polar areas. Only 3% of this freshwater supply is distributed on the mountains (Flint, 1971).This small amount is the support system sustaining the lives of millions and the economies of several nations. For the Indian sub-continent, these glaciers are the source of not just drinking water and irrigation but also a rich source of energy because the Himalayan glaciers are a source of perennial supply of meltwater to the streams and rivers draining down the valley and plains from the catchment areas. The 20$^{th}$ century has seen the large-scale changes in the glaciers globally. This century has witnessed a recession in the glaciers in the alpine regions across the globe. The first phase of this glacier retreat is related to the termination of the small glacial period within the 19th century that's on the brink of the 1850s. This retreat was an outcome of warming by 0.3°C within the last 25 years. A second 0.3°C warming has caused the hemisphere temperature to rise further compared to the last 1000 years (WWF, 2005). The temperature has been further predicted to extend within the Indian sub-continent by 3.5 and 5.5ºC by 2100 (IPCC, 2001a). The warmest years recorded are 1998 and 2005, with 1998 ranking first in one estimate, and 2005 slightly higher within the other two estimates (IPCC, 2007). It is estimated that 1ºC of temperature increase will cause the loss of 40% in terms of volume and more than 50% in volume as compared to 1850(IPCC 2001b). Himachal Pradesh is covered by western Himalayan ranges known as the Dhauladhar. This area receives very less rainfall from the South-West monsoon. The major form of precipitation is snowfall from the western disturbances. Therefore, this region is one of the biggest sources of energy trapped within fresh and permanent snow-cover.

## 3.2 DATA SETS

- All glaciers and lakes were digitized from Google Earth Pro for the Lahaul and Spiti district of Himachal Pradesh.
- For comparison between Lake Boundary and the amount of permanent snow cover over three decades, Landsat 1,5,7 and 8 images were used. The images were downloaded from https://earthexplorer.usgs.gov/. All the data, thus downloaded, belonged within a 20-day window to maintain consistency in the images and the dataset.

- SRTM 30m was downloaded from https://earthexplorer.usgs.gov/. This served as a reference for the outlet point of Sissu and Samudra Tapu glacial lake.

## 3.3 METHODOLOGY

After acquiring the required datasets, the images were stacked, mosaicked and clipped according to need. Therefore, to estimate change in glacier area and permanent snow cover following steps were taken:

- ○ Landsat FCC images were constructed for each decade and season. The glacial boundary was digitized manually using ERDAS IMAGINE 2014 and ARCGIS 10.5, respectively.
- ○ The digitized boundaries for two seasons in a year were overlaid and using the swipe function in ARCGIS 10.5, the permanent snow cover was identified.
- ○ The three sets of boundaries of the glaciers over the three decades were overlaid and the change in glacier area was identified. Thus, the quantity of glacial retreat was determined.

- There are several scientific methods used for the identification and mapping of glacial lakes based on images through remote sensing satellites. The identification or mapping could be done either through scientific empirical methods or visual identification. Normalized Difference Water Index (NDWI) is an important algorithm used to extract glacial lakes using satellite images of the time-period with minimum snow cover. Using the difference in the reflectance of different bands due to the different amounts of energy captured by the sensor and in turn producing different wavelengths produces variations in tone, texture color and shade in the images.
- Latitude Longitude: In ArcGIS 10.5, the X coordinate and the Y coordinates were calculated using: calculate geometry" option in the attribute table. The X coordinate gave the longitude and the Y coordinate gave the latitude. Since the majority of the lakes were less than 1 sq. km in area, instead of their latitudinal and longitudinal extension, the X coordinate and Y coordinate of the centroid was calculated.

- Area: In ArcGIS 10.5, within the attribute table, the area of the lake shapefile was calculated using “calculate geometry”
- Orientation: Using the Landsat FCC and the shapefile of the lakes, their orientation was manually decided upon. The lake’s inlet and outlet points were taken into consideration for the same.
- Altitude: Using SRTM DEM and the lake shapefile, the mean altitude was calculated. The “zonal statistics as table” function was used in ArcGIS 10.5 where mean altitude was calculated.

## 3.4 DEFINITION OF GLACIERS

Glaciers are a “rivers of ice” which flow down the slope under the influence of gravity. Fresh snow when falls at a particular place, it starts crystallizing. Fresh snowflakes start accumulating to form bigger crystals which over a period of time get heavier and stronger. This happens when the melting rate of the fresh cover is less than the snowfall. Therefore, fresh snow gets time to accumulate and hard form crystals of ice from snow grains. The topography of an area also decides the accumulation rate and subsequent formation of a glacier. A vast extensive stretch of flat land will aid in storing and accumulating fresh snow while a steep slope with lead to downward movement of the ice mass forming glaciers. Glacier masses receive ice form the snowfall as well as the liquid form (water vapor) that gets frozen at a higher altitude because of the ambient lesser temperature due to decreasing temperature by the lapse rate. But the major source of glacier formation is annual precipitation.

The extent, size, and degree of formation of glaciers is dependent on the ratio of accumulation and ablation. Every year the fresh snowfall of the winter months gets accumulated over the snow of previous years. In the summer season, the melting or ablation process works. This process continues where accumulation exceeds the ablation. Thus glacier is an outcome or ratio of rate of melting and accumulation exhibited by Equilibrium Line Altitude (ELA) that is an imaginary line bifurcating the zone or area of accumulation and ablation. Changing ELA means the changing mass balance of glaciers. Increasing ELA means retreating glaciers while decreasing ELA means advancing glaciers. Therefore, ELA is an indicator of the stability and health of glaciers. This health of glaciers is also reflected by snout of the glaciers. The snout of the glacier is a point from where melting of the glaciers start and marks the end of frozen ice mass. Snout of the glacier is a feature at a lower altitude where the surrounding temperature is higher than that of glacial body. These temperature differences or differential heating of the glaciers and its surrounding leads to glacial melt from a point. The case of advancing glaciers, the snout of the glacier is clean relatively with a bulging form while that of retreating glaciers is degraded and irregular. This change in snout position helps to develop an understanding of the chronology of the development stages of the glaciers historically in a region. But there is an occasional or seasonal change in the position of snouts as well. In the winter month there is a constant supply of fresh snow on the permanent ice cover while in summer ablation happens. This is an annual continuous cycle of advance and retreat. In the years when there is above normal snow-fall and a lesser degree of ablation, snout will see an extent. In the warmer years when there is less snow-fall, the reservoir of ice mass diminishes as the melting rate gets further accelerated but replenishment does not happen. On the contrary, during the colder periods, the supply increases and reaches till snout while there is little melting. This summer retreat is followed by flattening and temporary degeneration of the snout. In winters, it exhibits steep fronted clean glacier. This is a seasonal process that does not imply necessarily the change in glacial mass unless this becomes a period of successive loss.

In terms of activity, glaciers found in continental regions at higher latitudes are considered that remain spread out in vast flat stretches of land. While glaciers at higher altitudes in the lower latitudes are considered active due to the steep gradient.

## 3.5 STRUCTURE OF THE GLACIER SYSTEM

A typical valley glacier depicts two characteristic regions viz zone of accumulation and the other one is a zone of ablation. Between these two regions is an imaginary line called an equilibrium line of altitude that expresses the balance of the glacier region. Accumulation Zone: It's an area that receives the inflow or influx of fresh ice and snow over the previously lying surface. This year after year addition forms a thick zone which if devoid of moraine covers appears as a crystal white surface.

*Ablation Zone:* it’s an area that undergoes the loss of the stored ice meaning hereby the decrease in the mass of the glaciers due to melting, avalanches, erosion, calving etc. Since it's a zone of substantial loss, the surface area appears quite rugged and uneven with small ponds or meltwater stored on the surface.

*Equilibrium line of Altitude:* this represents the line of separation between a zone of ablation and accumulation. This is an expression of advancing or retreating glaciers. An increase in the ELA means a recession in the glacial mass while decrease in the ELA means advance in the glacial mass. ELA depicts the periodic balance of a glacier mass that is if there is an addition or reduction of the stored ice mass. Besides this, ELA also is an expression of the environmental or climatic variability within the particular region. An increase of snowfall and reduced melting means there is cooler microclimatic settings while enhanced melting rate demonstrates the warming of the region. This further leads to change in ELA.

*Snout of Glaciers:* This point marks an end of the glaciers that shows variable characteristics. In case of a glacier advance, the snout is clear and protruding in nature while in case of decrease it is rough and uneven. Depending on the rate of melting and freezing periodically, position of a snout changes and this forms precursor for the study of climatic cycle and its variability.

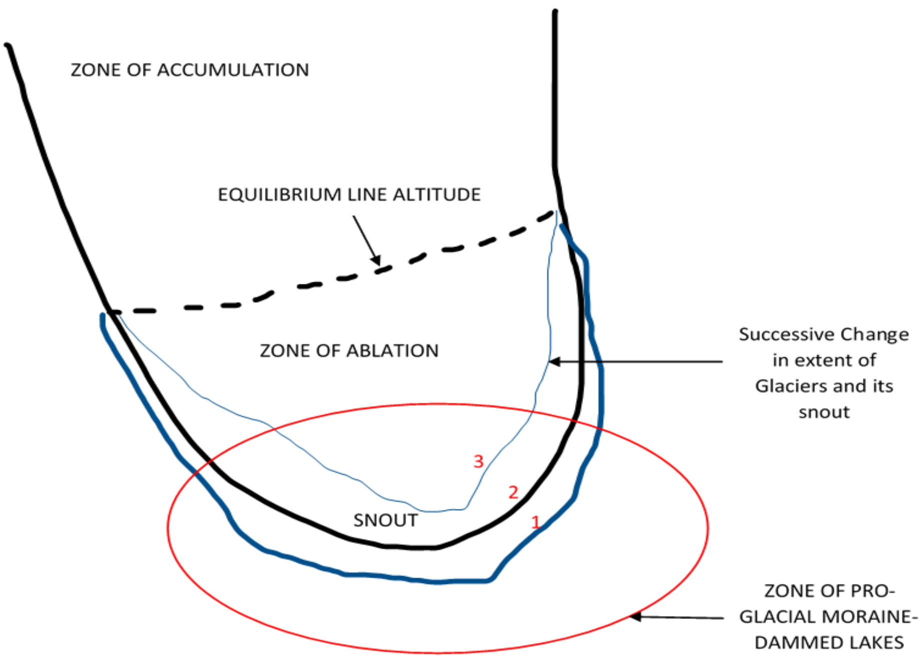



**Fig 3.1 Glacier System representing different zones of a typical valley glacier**

## 3.6 GLACIAL MOVEMENTS

Glaciers move at a very slow rate which at times is imperceptible. This movement also varies depending upon the type extent nature and geographical settings of the surroundings. Glaciers within the high altitudes of lower latitude is faster than those of higher altitudes. Since a glacier appears like a frozen river, its velocity, strength, erosive and transported power varies from the sides to the Centre. Also, glaciers exhibit movements in two ways one is the advancing movement of the glaciers and the other one is the movement within the ice mass in form of deformations. The altitude, topology and physiography of the region also play a crucial role in defining the velocity of the glacier. The velocity of the movement of the glacier is also directly proportional to the degree of slope. Besides the frontal or downward movement of the glacier, there is internal movement or deformation within the glaciers as well. From the margins towards the center velocity of the glacier increases too because of the lateral force and aggression acting towards the glaciers that decreases from margin to the center. From the surface downwards to the base also velocity decreases downwards. This is because of the pressure of the superincumbent layers that increases the thrust downwards which is why the movement at the surface is greater than the base. This is the reason most of the glaciers witness a sliding or gliding at the base.

## 3.7 HIMALAYAN GLACIER SYSTEM

Globally glaciers form an important reservoir of freshwater distributed unequally across the globe. Glaciers of high Asia constitute around 50 percent of the glaciers beyond polar areas. While 33 percent greater than that of glaciers in Europe (Jadish Bahadur, 2004).The glaciers are distributed widely within different morph-climatic regions and varied characteristics. Glaciers still hold over 70% of freshwater reserves on the terrestrial world. The Indian Himalayas have the maximum number of glaciers beyond Polar Regions with around 9575 glaciers (GSI, 2008). These Himalayan glaciers are the perennial source of Asia’s great rivers such as the Ganga, Indus, Brahmaputra, Salween, Mekong, Yangtze and, Huang Ho. Indus, Ganga and Brahmaputra. These rivers are the major source of the lives of the people of India and other riparian states. The entire economy is dependent on these perennial rivers. As per several scientific reports, it is calculated that 33,200 $km^2$ area of the Himalayas is glaciated occupying about 17 percent of the total area.

This glaciation process within the Himalayan is an outcome of the last ice age that is Pleistocene. This period underwent a series or cycles of glaciation and deglaciation representing periods of cooling and warming. These cycles became one of the reasons for a different types of glaciers. The present era is a period of glacial retreat. Physiographically, the Himalayan is a region with the most suitable required features. East-west alignment of the parallel ranges makes it a region with a zone of depression that receives precipitation in the form of snowfall due to the western disturbances. The impact of western disturbances decreases from west to east gradually. This is the season volume size and number of glaciers decrease from the west to east too. High altitude coupled with steep slopes experiences remarkably low temperature due to the adiabatic lapse rate of the rising rarefied cold air mass. Besides the northern slope receives lower insolation than that of the southern slopes. South to the north also there is a substantial increase in altitude and decrease of temperature of that decreases the melting rate of the glaciers. Therefore, there is a successive accumulation of fresh snowfall added to the previous layers year after year. But Lahaul & Spiti region is contiguous with Ladakh, area geographically forming a dry barren cold desert area devoid of vegetation due to scanty precipitation. While eastern Himalayan parts in Nepal and Southern parts in southern Himachal Pradesh and Uttarakhand are glaciated regions with a lower tree line. Due to the complex set of factors, there is remarkable variation in the size of the glaciers across the whole Himalayan region. It ranges from Siachen glacier being the largest glacier to small Gangstang glacier in Himachal Pradesh.

## 3.8 CLASSIFICATION OF GLACIERS

### *3.8.1 Thermally, glaciers are of 3 types: temperate, subpolar and polar*

Temperate glaciers are relatively warmer and discharge large amounts of meltwater in melting seasons. Sub-polar also discharges water but due to lower atmospheric temperature, gets refrozen again. And remaining water flows down sub-glacially. In the polar areas, atmospheric temperature is below freezing throughout the year. Therefore, there remains a permanent ice cover. This classification is based on the latitudinal extent which receives differential insolation.

### *3.8.2 Classification of Glaciers on the basis of Morphology*

Glacier cover of the present day is only a minuscule representative (only 1/3) of the massive *Ice Age* glaciations that covered almost 30% of the world surface area. The handiwork of these *Ice Age* glaciations is omnipresent as the spectacular landscape, be it the Swiss-Austrian Alps or the Higher Himalaya. Contemporary glaciers still cover an approximate area of 14.9 million km$^2$, including the continental glaciers of Antarctica and Greenland, to tropical Africa. As mentioned earlier, the occurrence of glaciers is a function of precipitation falling as snowfall and an annual rate of melting, which is determined by temperature and nature, type and timing of precipitation. The existence of glaciers is conditioned not only by climate but also by topography and relief, for there has to be a suitable surface on which ice can grow. For instance, India receives a large amount of precipitation during the summer months when the ambient temperatures are very high. On the other hand, winter precipitation, however small, may be more useful for the sustenance of glacier bodies. Therefore, the seasonal distribution of precipitation is more crucial than the total amount. The Himalayan glaciers are the result of immense relief, seasonality and type of precipitation, and necessary available topography. Glaciers of Himachal Pradesh can also be classified based (Figure 3.4) on the morphological character, besides temperature conditions that are *Cirque glaciers, valley glacier, mountain, ice cap and mountain basin glaciers.* This varied morphology is because of underlying geological structure, topography, denudation process altering and modifying this immediate topography and also the meteorological conditions. Since climate decides the rate, duration and extent of snow accumulation. Since all the river basins have different geologic, physiographic, climatic and other environmental parameters, the distribution of types of glaciers also differs in each basin. Basins with high altitudinal ranges predominantly receiving more precipitation have high accumulation areas. The orientation, slope of the region also decides the rate of melting i.e. ablation of the glacier. All these factors cumulatively decide the type of glaciers in a basin. The glaciers in the inventory include the following types, typical to Alpine Himalayan environment.

1) **Cirque glaciers:** Cirque glaciers are small ice masses generally occupying an amphitheater-shaped bedrock hollow, with a width-length ratio of 1:1. Such glaciers are normally found to be the remnants of large tributary glaciers of the

Local Last Glacial period, with lateral sedimentary extent reaching considerable distances in the Himachal Himalayas. Such types of glaciers are found at the higher altitudes within amphitheaters.

**Plate 6: Cirque glacier in Milang Valley, Lahaul & Spiti**

**2)** **Mountain Glacier:** Mountain glaciers need not necessarily occupy the same shape as cirques but are elongated, having a width-length ratio of 1:2 or more. These glaciers are normally of any shape but smaller and close to a valley type, on sharper gradients. Such glaciers appear to have better sustenance being at higher altitudes where the double-peak effect is pronounced, and with ablation surface strongly restricted. This type has a single arm. Such ice masses may be in large numbers but total coverage is always small. These may, at times, cause ice-avalanches. Sometimes these are referred to as hanging, niche or glaciers as well.

**Plate 7: A mountain glacier on the Chandrabhaga (CB) range**

3) **Mountain Basin Glacier:** Mountain basin glaciers are defined as the large ice-bodies that do not necessarily occupy a valley but cover large areas in undefined shape in a ratio of 1: 3 or more. These are peculiar glacier features with two or more tributaries in the higher slopes of the mountains.

**Plate 8: Typical mountain basin glacier in Himachal Pradesh**

4) **Ice Cap:** Ice caps are on the mountain tops in a sheet-like form. At times, ice caps have radial growth and flow in to either side such as the Gangstang glacier in the Chandrabhaga basin. Such ice bodies cover a small fraction of the total covered area.

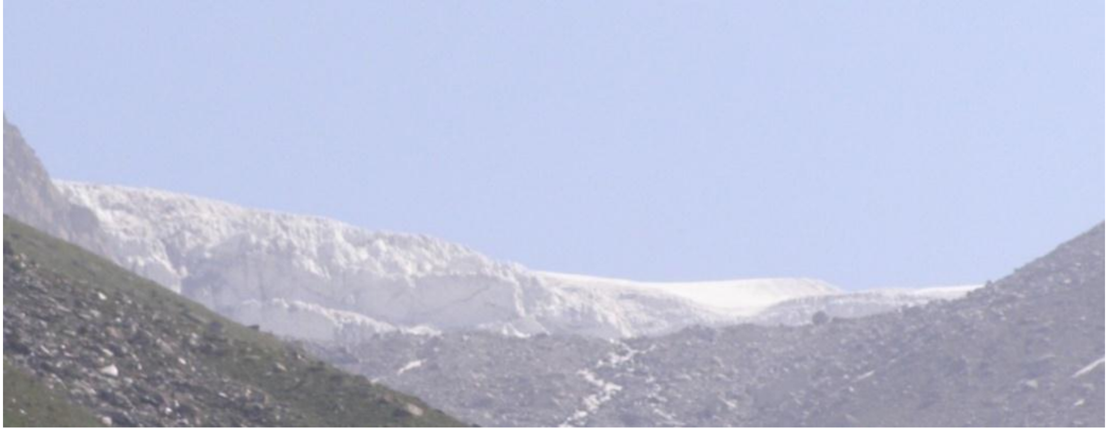


**Plate 9: Ice cap in Urgos valley, Miyar basin in Lahaul & Spiti**

5) **Valley Glacier:** The valley glaciers flow down in a well-defined terrain which may at times be formed by the merging of many tributary glaciers along the length. These glaciers are also known as compound and simple basin types, depending on the number of tributary glaciers feeding into the main trunk glacier. Such glaciers have the largest areal coverage.

**Plate 10: Mulkila valley glacier on the CB range**

6) **Unclassified/ Rock glacier:** This category of glaciers might not exhibit ice cover at any of its surfaces but generally are ice-injected and flow in the same manner as the other glaciers. The only difference is the quantity of boulders and sediments which might be as large as 95% of the total size. These rock glaciers and rock glaciered surfaces are at the transitional zone between the semi-humid Great Himalayan and arid t sub-arid Zaskar range. These have not been taken into account for the present analysis.

**Plate 11: Rock glacier near the Baralacha Pass**

## 3.9 CHARACTERISTICS OF GLACIERS IN THE HIMALAYAS

Himalayan mountain system is a network of a series of parallel ranges aligned east to west. These different parallel ranges have a varying altitudinal ranges with different geological, climatological, topographical and vegetation features. This range and variation make it different from the glaciers of Africa, Europe and parts of Asia. Some of the characteristic features of the Himalayan glaciers are:

i) Large parts of Himalayan glaciers are covered with debris cover. A large quantity of boulders, pebbles, rocky uneven surface constitutes the area as well.

ii) Lower part of the glaciers that are ablation areas witness a lot of human influence and intrusion.

iii) High snow line and dynamic ELA is a important aspect of Himalayan glaciers.

iv) Rockfall, debris flow, avalanches are regular phenomenon in Indian Himalayas due the crustal instability caused by the movement of Indian and Eurasian plates.

## 3.10 ROLE OF THE HIMALAYAN GLACIER ON ECONOMY

Himalayan glaciers are a major source of freshwater availability within the Indian sub-continent. These are the source feeding all the major perennial rivers in the sub-continent. Besides the rainfall, glacial meltwater constitutes the major input to these perineal rivers when during the spring and summer season ablation of glacial ice mass supply water to the plains through the network of the great Indian River system. Therefore, Himalayan glaciers are an important constituent of the northern drainage system. Agriculture is the major economic form and type practice within the sub-continent and this agrarian society provides livelihood to billions of population. Along with rain-fed irrigation, canal irrigation is another major source that is dug out of the perennial rivers. This is essential to maintain and sustain the billions of people. Besides irrigation, drinking water supply is also dependent on this.

The Himalayan system of glaciers is also a storehouse of hydroelectricity. It has a vast potential of untapped hydroelectricity which if utilized at the optimum level it could sustain a major chunk of the economy of the whole nation. In the time of sustainable development where every nation is looking for a sources of clean energy, the Himalayan regions prove to be the great reservoir of hydroelectricity providing alternatives to conventional energy.

Besides the importance of glaciers in terms of drainage and economy, it also acts as a litmus test to know the balance of the natural environment. Glaciers are sensitive even to the slightest change in the atmospheric conditions. Therefore, direct and indirect studies of the glacier dynamism can provide information on the variability and fluctuations of the local climatic conditions. Glaciers and associated features also act a guide for paleo-climate reconstructions. Change in position of snout, shifting ELA, and dispersion of glacial features provide an image of the past atmospheric conditions and predict the future projections. Himalayan Glaciers also have a neutralizing effect on the temperatures of north India at the same time act as a barrier from the cold polar blizzards and western disturbances. Glacier dynamism is an expression of the complex set of responsible factors that subsequently help to understand comprehend and analyze the climatic changes. Further, it can act as a tool for the policymakers to plan devise strategies policies and mechanisms to curb and minimize environmental damage.

## 3.11 INVENTORY OF THE GLACIERS IN HIMACHAL PRADESH

Himachal Pradesh as the name implies is the storehouse of snow and ice. It is home to more than thousands of enormous glaciers. The lesser Himalayan and the Great Himalayan Ranges abode all these glaciers. Within Himachal it is the districts of Lahaul and Spiti, Kullu, Kinnaur, few upper areas of Kangra region and Chamba only that have glaciers. Out of these, Lahaul and Spiti have the maximum share of the Glaciers. In all, (Table 3.1) Himachal Pradesh has 2189 glaciers. While if we look at the basin-wise distribution, it is the tributaries of Indus viz: Chenab, Sutlej, Ravi and Beas flowing between the Great and middle Himalayas from north and north-east to western side. Chenab basin has the maximum number of glaciers that is 813 followed by Satluj 657 and Beas 346. The least is in the Yamuna basin 17 (Table 3.1).Morphologically, mountain types, valley type and cirque type predominate while the least is the rock glacier ( Table 3.2)

| **Basin** | **Total Number of Glaciers** |
|---|---|
| **Beas Basin** | 346 |
| **Chenab Basin** | 813 |
| **Ravi Basin** | 225 |
| **Satluj Basin** | 657 |
| **Tsarap Chhu Basin** | 80 |
| **Yamuna** | 17 |
| **Bhagirathi** | 33 |
| **Total** | 2189 |

**Table 3.1 Basin wise Distribution of Glaciers in Himachal Pradesh**

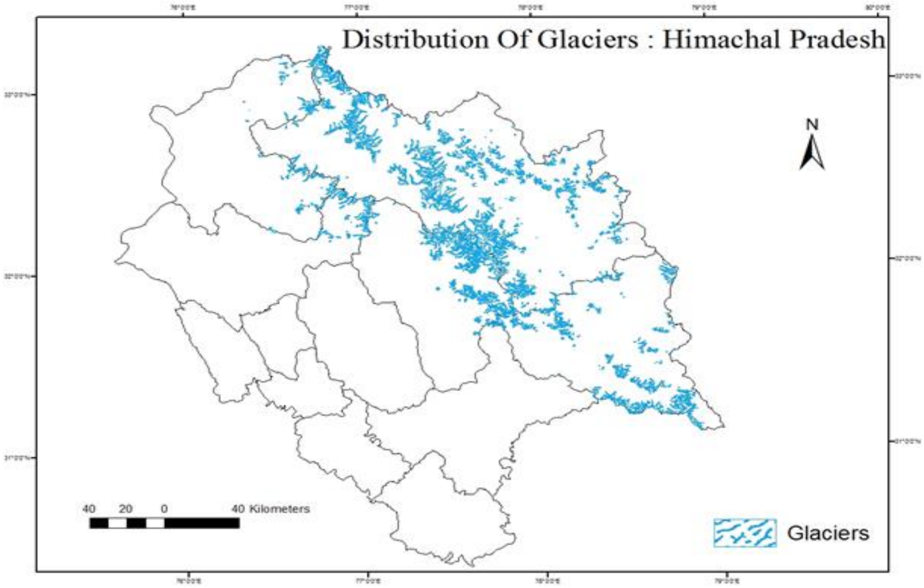



**Fig 3.2 Distribution of Glaciers in Himachal Pradesh (2020)**

| | |
|---|---|
| Cirque type (C) | 12 |
| Hanging Glacier (Mh) | 109 |
| Mountain Niche type (Mn) | 1663 |
| Rock Glacier (R) | 24 |
| Valley type (V) | 381 |
| Total number of Glaciers | 2189 |

**Table 3 .2. Glacier types and number of glaciers in the Himachal Pradesh.**

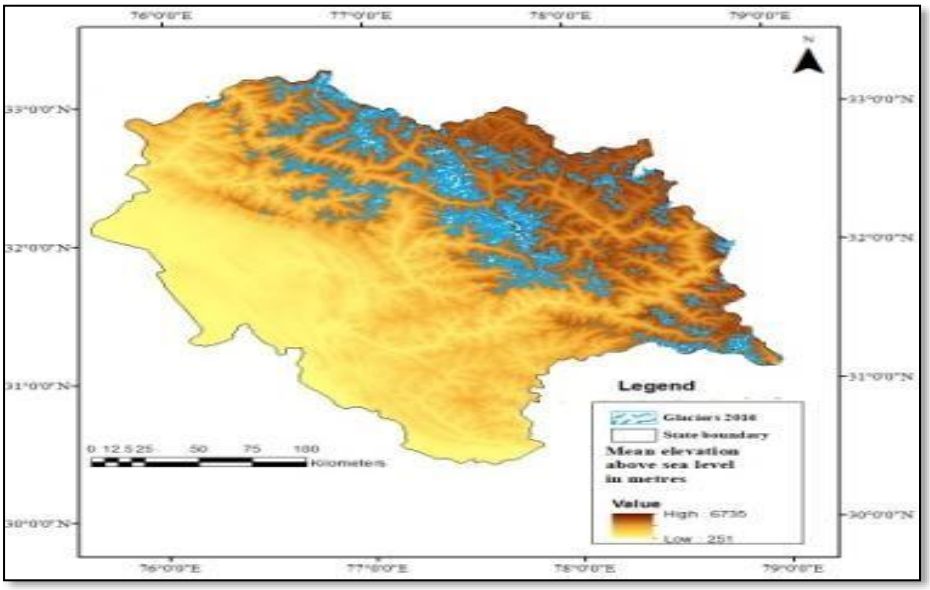



**Fig 3.3. Distribution of Glaciers in Himachal Pradesh Overlaid on Elevation map.**

## 3.12 GLACIER DYNAMISM AND CHANGES

Glacier cover dynamics for two decades between 2000-2019, is administered for the basins of Beas, Chenab, Ravi, Sutlej and Tsarap Chhu (Indus sub-basin). Among the watersheds analyzed, Chenab contains the utmost area under glacier cover, constituting ~1204 km2. The smallest amount and area under glacier cover is that within the watershed of Tsarap Chhu, a rain-shadow region of ISM within the Indus basin, with approximately ~58 km2, a neighborhood of Himachal Pradesh. Yamuna basin otherwise has the smallest amount of glacier cover amounting to approximately ~97 km2 when small watersheds of this administrative boundary is taken into account. Such differences within the glacier extent of Chenab and Yamuna are often attributed to the presence of various climatic regimes and therefore the differences in elevation as an influencing factor. To mention the smallest amount, any location, orientation and slope angles are micro-regional factors that influence an individual glacial dynamics.

| Basin | Glacier Area ($km^2$): 2000 | Glacier Area ($km^2$): 2016 | Change in Area (Δ) $km^2$ 2000-2016 | % (Δ) in Area 2000-2016 | Glacier Area ($km^2$): 2019 | Change in Area (Δ) $km^2$ 2016-2019 | % (Δ) in Area 2016-2019 | Change in Area (Δ) ($km^2$) 2000-2019 | % (Δ) Change in Area 2000-2019 |
|---|---|---|---|---|---|---|---|---|---|
| **Beas** | 440.15 ± 0.06 | 435.61 ± 0.07 | 4.54 ± 0.07 | 1.03 | 432.34 ± 0.06 | 3.27 ± 0.06 | 0.75 | 7.81 ± 0.10 | 1.77 |
| **Chenab** | 1204.91 ± 0.08 | 1192.71 ± 0.08 | 12.20 ± 0.08 | 1.01 | 1194.28 ± 0.08 | -1.58 ± 0.07 | -1.58 | 10.63 ± 0.10 | 0.88 |
| **Ravi** | 158.84 ± 0.03 | 157.56 ± 0.03 | 1.28 ± 0.03 | 0.81 | 157.57 ± 0.03 | -0.03 ± 0.03 | -0.02 | 1.26 ± 0.03 | 0.79 |
| **Satluj** | 748.85 ± 0.05 | 743.96 ±0.05 | 3.89 ± 0.05 | 0.52 | 744.6 ± 0.05 | 0.37 ± 0.05 | 0.05 | 4.26 ± 0.05 | 0.56 |
| **Tsarap Chhu** | 57.75 ± 0.03 | 57.38 ± 0.03 | 0.43 ± 0.03 | 0.74 | 57.6 ± 0.03 | -0.22 ± 0.03 | -0.38 | 0.15 ± 0.03 | 0.25 |
| **Yamuna** | 98.66 ± 0.05 | 96.71 ± 0.05 | 1.94 ± 0.05 | 1.97 | 96.57 ±0.05 | 0.15 ± 0.01 | 0.16 | 2.10 ± 0.11 | 2.13 |

**Table 3.3. Glacier Change statistics for HP**

Within Himachal Pradesh, the least amount of change in glaciated has occurred in the Satluj basin, with a change of only 0.52% between 2000-2016. The highest amount of change is noticed in the monsoon-dominated watershed of Beas, with a value of 0.87% within the same period. Barring Satluj, there exist a close similarity in percentage reduction of glacier cover in all the watersheds of Himachal Pradesh, with values tending to 0.8% approximately. Among the watersheds analyzed, Chenab contains the maximum area under glacier cover, constituting ~1204 $km^2$ in Himachal Pradesh. The least area under glacier cover is that in the watershed of Tsarap Chhu, a rain-shadow region of ISM in the Indus basin, with approximately ~58 $km^2$, a part of Himachal Pradesh. Yamuna basin otherwise has the least glacier cover amounting to approximately ~97 $km^2$ when small watersheds of this administrative boundary are considered. Such differences in the glacier extent of Chenab and Yamuna can be attributed to the presence of different climatic regimes and the differences in elevation as an influencing factor. To say the least, any location, orientation and slope angles are micro-regional factors that influence individual glacial dynamics. The highest percentage change in glaciated is observed in Yamuna watershed during analysis period. With a percentage reduction of 1.97% of its glacier area between 2000 and 2016; the Yamuna watershed demonstrates vulnerability to a possibility of changing climatic dynamics at a lower latitude. Strong regional variations in the values of percentage change of glacier areas also exist within the monsoon dominated climatic regimes; which can be attributed to micro regional factors which determine the rates of change. Amongst the basins under purview, maximum reduction in glacial area has occurred in the Beas Basin (1.77%), which is bounded by the Pir Panjal; and is categorized under the monsoon climatic regime. It is interesting to note the similarity in the orientation of valley directions of the Yamuna and Beas basins.

### *3.12.1 The Chenab Basin*

Glaciers of the Chenab basin have been classified on the variety of parameters for assessing changes during the period 2000-2019. The total loss in glacier cover within the basin is approximately 10.63 $km^2$ for a period of 20 years (2000-2019) (Figure 3.4). These glaciers have been grouped according to the area, slope angle, and aspect classes. This basin lies at the junction between two very dissimilar climatic regimes, the Indian Summer Monsoon (ISM) that brings in summer liquid precipitation, and the Mid-Latitude continental type climate which brings in solid precipitation in the winters. After the initial downpour of the summer monsoon on the southern slopes of the Pir Panjal, very little moisture cross over to the north. Hence, the region to the north does not face much of the summer precipitation from the summer monsoon rainfall due to such an orographic mechanism. However, the Mid-latitude Westerlies do bring in a large amount of solid precipitation in the winter months in this E-W trending basin which accumulates as seasonal snow. Almost the entire water requirement of the basin and beyond is thus dependent on the glacier reserve.

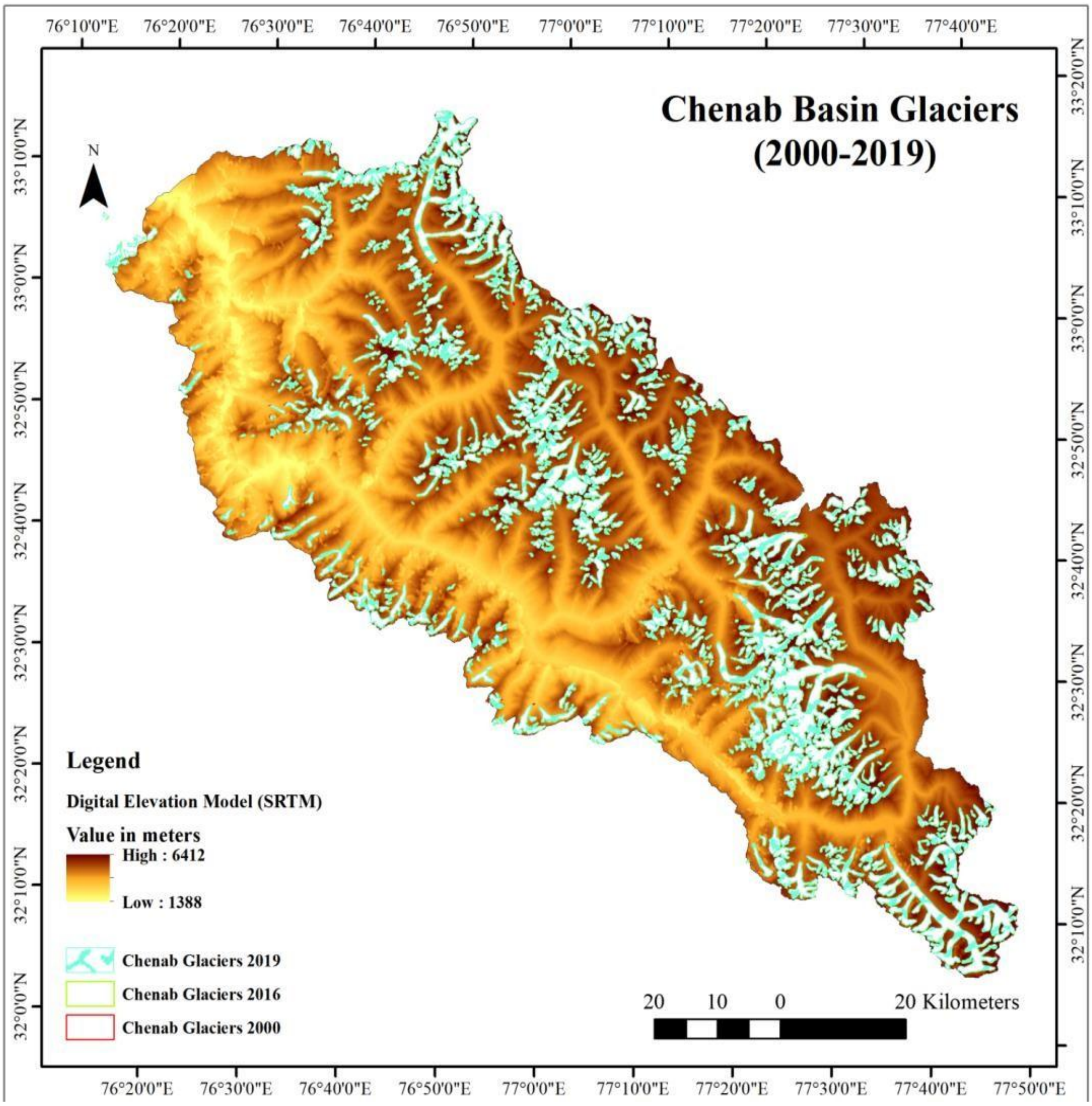


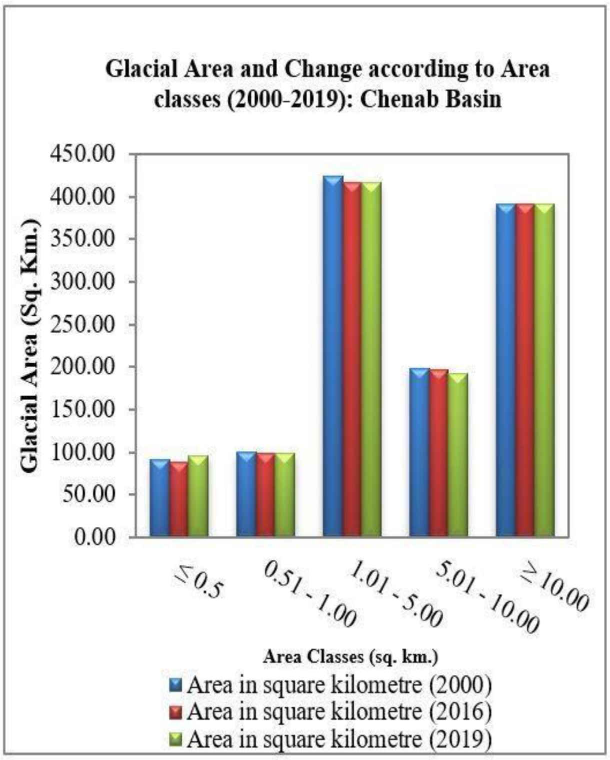

**Fig 3.4. Glacier distribution and changes in Chenab Basin (2000-2019)**

### *3.12.2 Changes in the Glacier Area According to the Size*

Classification is based on size-class with ≤ 0.5 km$^2$, 0.51 to 1.00 km$^2$, 1.01-5.00 km$^2$, 5.0110.00 km$^2$and >10.00 km$^2$, respectively. The first category represents the smallest glaciers located on the higher elevations and in small pockets as glaciers and niche types. The increase in total glacier area within this class amounts to approximately 5.31 km$^2$ over a period of 20 years (2000-2019). The initial loss for 17 years (2000-

2016) was calculated at 2.25 km$^2$, but in the subsequent years, it increased by ~7.56 km$^2$ between 2016-2019.

The smallest glacier area-class reflects a considerable increase in areal coverage. The smallest glaciers in the basin constitute a total of 432 glaciers which show a 7.56 km$^2$ increase, with the 8.51% change (Fig.3.5).



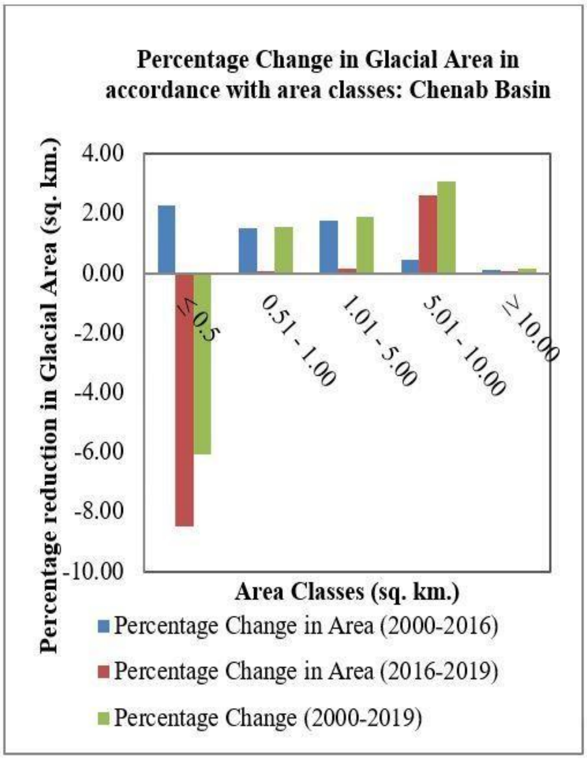




**Fig. 3.5. Glacier Changes according to Size-Class in the Chenab Basin (2000-2019).**

Discernible negative changes have been noticed in the area-class of 5-10 km$^2$, with a value of 2.63% from 2000-2016 to 3.06% from 2016-2019, followed by the area-class of 1-5 km$^2$, with 1.88% in 2000-2019. However, the larger glacier categories of 1.01-5, 5.01-10 and > 10 km$^2$ show an initial loss of 7, 1, and 3 km$^2$ of area over 200-2016, but subsequently regained marginally between 2016-2017.This is maybe the effect of an increase in solid winter precipitation which does not wither too fast (Figure 3.5, Table 3.4 ).

| Area Class km$^2$) | Area (km$^2$) (2000) | Area (km$^2$) (2016) | Change in Area (Δ) (km$^2$) 2000-2016 | % change in Area 2000-2016 | Area (km$^2$) (2019) | Change (2016-2019) | % change in Area 2016-2019 | Change (2000-2019) | % change in Area 2000-2019 |
|---|---|---|---|---|---|---|---|---|---|
| **≤ 0.5** | 90.88 ± 0.01 | 88.82 ± 0.01 | 2.05 ± 0. 0002 | 2.255722 | 96.38 | -7.56 | -8.5116 | -5.51 ± 0.27 | -6.06 |
| **0.51 - 1.00** | 99.95 ± 0.04 | 98.44 ± 0.03 | 1.52 ± 0.0006 | 1.52076 | 98.41 | 0.03 | 0.030475 | 1.54 ± 0.07 | 1.54 |
| **1.01 - 5.00** | 424.17 ± 0.11 | 416.79 ± 0.11 | 7.38 ± 0.0019 | 1.739868 | 416.18 | 0.61 | 0.146357 | 7.98 ± 0.39 | 1.88 |
| **5.01 - 10.00** | 197.94 ± 0.34 | 197.03 ± 0.34 | 0.91 ± 0.0016 | 0.459735 | 191.86 | 5.17 | 2.623966 | 6.08 ± 0.30 | 3.06 |
| **≥ 10.00** | 391.97 ± 1.37 | 391.63 ± 1.37 | 0.34 ± 0.0092 | 0.086741 | 391.45 | 0.17 | 0.043408 | 0.52 ± 0.02 | 0.13 |

**Table 3.4. Glacier Change Statistics (Area-Class) in Chenab Basin (2000-2019)**

### *3.12.3 Changes in the Glacier Area According to the Aspect*

Between the 2000-2016 periods, the greatest amount of absolute glacial area loss is recorded as ~5.13 km$^2$ in the glaciers with north-eastern aspect, followed by south and south-west with absolute area loss of ~2.81 and ~2.20 km$^2$, respectively. The percentage figures however show the maximum amount of change of ~2.53 km$^2$ and 2.82 km$^2$ in the south and south-west aspect. The least percentage of changes is observed in the glaciers with an eastern aspect. In the time span of 20 years, the maximum loss in glacier area has been seen in the southern and south-western aspects, with a percentage reduction of ~2.06% and 2.57%, respectively. A total of 98 glaciers with orientation to the east show no overall change in area over the years 2000-2019 (Table 3.5; Figure 3.6).

| Aspect | Area in 2000 | Area in 2016 | Area in 2019 | Glacial Area Loss (km$^2$) (20002016) | Glacial Area Loss in percentage (2000-2016) | Glacial Area Loss (km$^2$) (20162019) | Glacial Area Loss in percentage (2016-2019) | Total Glacial Area Loss in (2000-2019) | Total Glacial Area Loss in percentage (2000-2019) |
|---|---|---|---|---|---|---|---|---|---|
| **N** | 15.77 | 15.63 | 15.67 | 0.14 | 0.92 | -0.04 | -0.25 | 0.10 | 0.64 |
| **NE** | 402.90 | 397.77 | 397.76 | 5.13 | 1.27 | 0.01 | 0.00 | 5.14 | 1.28 |
| **E** | 207.86 | 207.17 | 207.86 | 0.69 | 0.33 | -0.69 | -0.33 | 0.00 | 0.00 |
| **SE** | 70.75 | 69.23 | 69.54 | 1.52 | 2.15 | -0.31 | -0.45 | 1.21 | 1.71 |
| **S** | 97.34 | 94.88 | 95.33 | 2.46 | 2.53 | -0.45 | -0.48 | 2.01 | 2.06 |
| **SW** | 69.46 | 67.50 | 67.67 | 1.96 | 2.82 | -0.18 | -0.26 | 1.78 | 2.57 |

**Table 3.5. Glacier Change Statistics (Aspect-Wise) in Chenab Basin (2000-2019)**

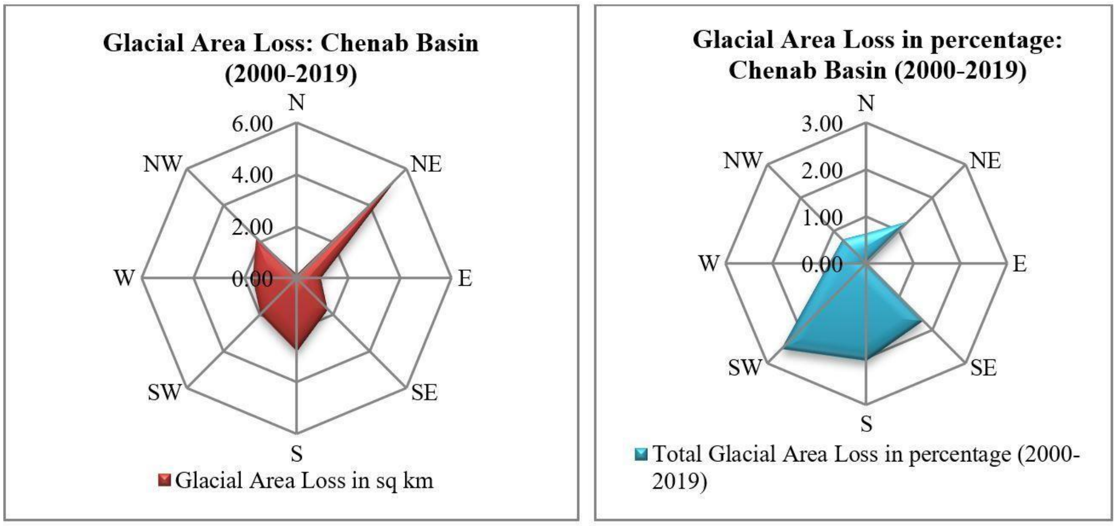



**Fig. 3.6. Glacier Changes According to Aspect in Chenab Basin (2000-2019).**

### *3.12.4 Changes in the Glacier Area According to the Slope*

An angle of channel floor slope strongly influences the glacial dynamics, especially when studied over a temporal scale. Considering that other variables remain favorable, there exists a positive relationship between the angle of slope and the glacier retreat; given the other variables are constant (Fig. 3.7)

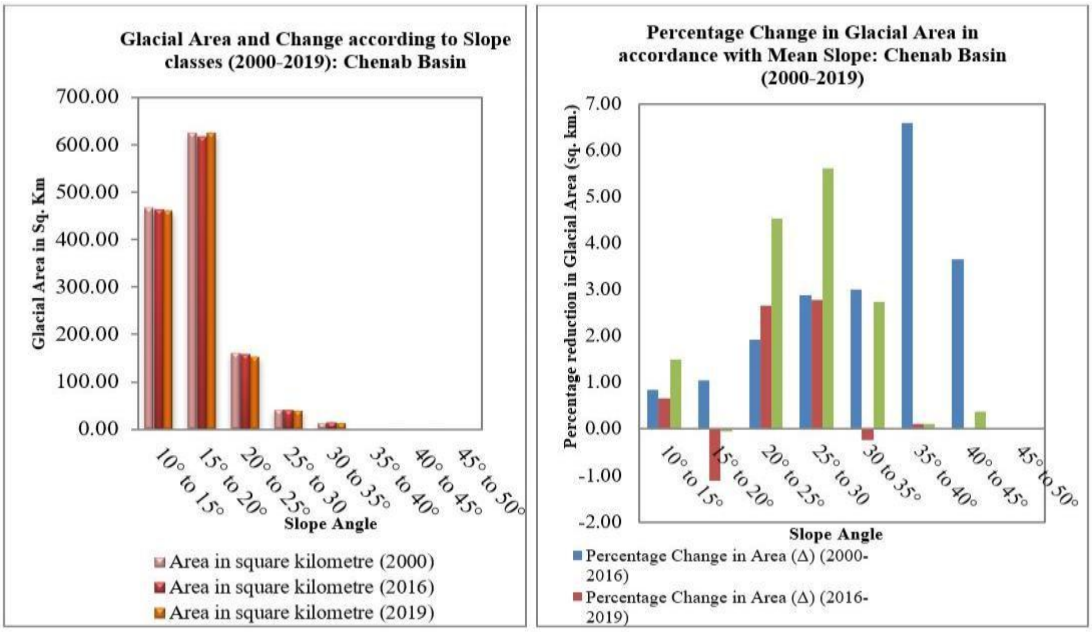



**Fig 3.7. Glacier Changes According to Slope-Class in Chenab basin (2000-2019).**

### *3.12.5 Glacial Inventory and Changes through Angle Class*

Within the Chenab basin, the maximum amount of change in the glacier area has been observed in the angle-class of 35° to 40°, with a change of ~6.59% from 2000-2016; and 0.94% from 2016-2018. The angle classes of 45° to 50° show no visible change in the glaciated area as they are mainly rock glacier of a minimal extent with only 0.5km$^2$ of area. The lower angle classes reflect very little changes in the glaciated area as they are large valley glaciers, which are few with low percentage reduction, but with high absolute figures (Table 3.6).

However, it is interesting to note that the valley glaciers with a larger area show an apparent increase in the cumulative glaciated area between 2016-2019, with a small gain in the coverage.

| Slope Class | No. Of Glaciers | Area (km$^2$) (2000) | Area in square kilometre (2016) | Change in Area (Δ) (km$^2$) (2000-2016) | % Change in Area (Δ) 2000-2016 | Area (km$^2$) (2019) | Change in Area (Δ) (km$^2$) (2016-2019) | % Change in Area (Δ) (2016-2019) | Change in Area (Δ) (km$^2$) 2000-2019 | % Change in Area (Δ) 2000-2019 |
|---|---|---|---|---|---|---|---|---|---|---|
| **10° to 15°** | 84 | 466.9802 ± 0.2779 | 463.0518 ± 0.2756 | 3.9283 ± 0.0023 | 0.84 | 459.98 ± 0.2750 | 3.07 ± 0.001 | 0.66 | 7.00 ± 0.01 | 1.50 |
| **15° to 20°** | 279 | 623.0767 ± 0.1116 | 616.5511 ± 0.1104 | 6.5255 ± 0.0011 | 1.04 | 623.36 ± 0.1100 | -6.81 ± 0.001 | -1.10 | -0.28 ± 0.001 | -0.05 |
| **20° to 25°** | 233 | 160.8482 ± 0.0345 | 157.7579 ± 0.0338 | 3.0902 ± 0.0006 | 1.92 | 156.56 ± 0.0334 | 4.20 ± 0.001 | 2.66 | 7.29 ± 0.01 | 4.53 |
| **25° to 30** | 131 | 40.5450 ± 0.0154 | 39.3734 ± 0.0150 | 1.1715 ± 0.0004 | 2.88 | 39.28 ± 0.0150 | 1.09 ± 0.002 | 2.78 | 2.27 ± 0.006 | 5.60 |
| **30 to 35°** | 64 | 14.1308 ± 0.0110 | 13.7068 ± 0.0107 | 0.4239 ± 0.0003 | 3.00 | 13.74 ± 0.0106 | -0.03 ± 0.001 | -0.24 | 0.38 ± 0.001 | 2.73 |
| **35° to 40°** | 15 | 1.1444 ± 0.0038 | 1.0689 ± 0.0035 | 0.0754 ± 0.0002 | 6.59 | 0.97 ± 0.0034 | 0.10 ± 0.0002 | 9.78 | 0.17 ± 0.001 | 15.32 |
| **40° to 45°** | 6 | 0.3442 ± 0.0028 | 0.3316 ± 0.0027 | 0.0125 ± 0.0001 | 3.65 | 0.29 ± 0.0025 | 0.04 ± 0.0001 | 12.56 | -0.25 ± 0.001 | -861.82 |
| **45° to 50°** | 1 | 0.0568 ± 0.0014 | 0.0568 ± 0.0014 | 0 ± 0.00 | 0 | 0.01 ± 0.0014 | 0.03± 0.00 | 67.69 | 0.04 ± 0.001 | 68.77 |

**Table 3.6. Glacier Change Statistics (Angle-Class) In Chenab Basin (2000-2019)**

| S.NO | Elevation Maximum | Elevation Minimum |
|---|---|---|
| Mean | 5519.54 | 4957.17 |
| Range | 2425.90 | 2687.70 |
| Minimum | 4158.60 | 3624.90 |
| Maximum | 6584.50 | 6312.60 |
| Sum | | |

**Table 3.7 Altitudinal range and expanse of glaciers in Himachal Pradesh**

There is great variation seen in the aerial extent of the glaciers as well as in terms of the altitude. The Highest glacier reaches up above 6584 meters while the lowest in height being 4158 meters. In terms of area, the largest glacier occupies up to 124 $km^2$ while the least area is only 0.4 $km^2$ (Table 3.8).

## 3.13 INVENTORY OF THE GLACIAL LAKES IN LAHAUL AND SPITI

Climate change is a burning issue of late at the international platform within academicians, the scientific community and the policymakers. Climate change is believed to cause variability in climatic parameters and alterations in geomorphic features. Climatic changes across the world are responsible for the enhanced melting of glaciers across the planet. This enhanced melting of glaciers leads to the way of formation of glacial lakes at different places. Therefore, there is a gradual increase in the number of small glacial lakes at several places. Indian Himalayan is no such exception. Besides these new lakes, there are several lakes that are the byproduct of the Little Ice Age (1400-1650 AD). Due to advancement and subsequent melting of the glaciers paved the way of the formations of glacial lakes. These newly formed glacial lakes of the Little Ice Age lead to Glacial Lake Outburst Floods (GLOFs). These outburst floods have far-reaching devastating impacts damaging lives and infrastructure worth millions of rupees. Outburst floods cause even more destruction downstream the valley because of the availability of the large glacial born boulders and rock fragments etc. GLOFs is one of the devastating hazards though there are many such as avalanches, landslides, rock calving etc. Potential of GLOFs is believed to increase in the future which eventually can lead to the collapse of the area under impact. In Spite of the severity of threat, there is dearth of detailed study of glacial lakes in whole region and comprehensive analysis of the mechanisms of GLOFs and the factors responsible for its occurrence. In order, to prepare mitigation efforts and strategize reduction measures, it is imperative to prepare an inventory of glacial lakes depicting its spatio-temporal extent location and size. This information provides the basis for mapping and zoning of hazard prone areas. Paleo conditions and future projections of the glacial region and associated features prove essential to generate atmospheric ion predictions and hazard assessments. Since the Himalayan region has difficult terrain and inaccessible and inhospitable location, field investigation becomes a rare phenomenon. Therefore, remote sensing along with Geographic Information System (GIS) become an important aid to provide more precise and accurate information of the glaciers and glacial lakes with their changing spatio-temporal extent.

Lahaul & Spiti, two contrasting physiographic regions of Lahaul & Spiti administrative district form a part of the Trans-Himalayan and Greater Himalayan range. This is rich in the dense network of large and small glaciers and glacial lakes. Lahaul & Spiti in the state has the maximum number of glacial lakes.

### *3.13.1 Definitions of A Glacial Lake*

Glacial Lake is a volume of the meltwater of the glaciers existing with sufficient quantity in a depression area of glaciers formed in, under, beside and/or in front of a glacier by different glacial activities and/or retreating processes of a glacier (Yamada, 1991) (Yamada & Sharma, 1993) (Mool, Bajracharya et al, 2001) (Raj & Kumar, 2016).It is an important feature of the glacier environment. Any impoundment or storage of water mass near or at the vicinity of glacial or periglacial environment forms a part of glacial lake. It could be formed due to different reasons. Glacial lakes are highly dynamic and variable geomorphic feature. The Himalayas and particularly Himachal Pradesh have a number of glacial lakes of the varying dimensions. In terms of origin, geology, hydrologic, geomorphic and other physical parameters. These glacial lakes are spread across varying range of altitudes with a stark range in slope and aspect features with lakes at higher altitudes having different while the ones at lower altitudes have different features. Of late with increasing an influx of tourism, glaciers and glacial lakes have gained prominence in popular culture. These are an increasing facing the impact of anthropogenic activities closer to the glaciers affecting the natural setting. These glacial lakes sometimes form the source of water to the locals along with acting as a balancing mechanism of the ecosystem of the glacial region.

### *3.13.2 Types of Glacial Lakes*

Various experts have attempted to classify glacial lakes. (Embleton & King, 1975) (Mool, Bajracharya, & Joshi, 2001) (Raina, 2008) (Rai, Bakshi, & Garg, 2012). A glacial lake can be delineated based on some important factors i.e. physical characteristics, association with the nearby glacier and the surrounding features (Ashraf, Naz, & Iqbal, 2015). The glacial lakes can be classified broadly into four types i.e. moraine-dammed, ice-dammed, erosion and, other glacial lakes (ICIMOD, 2011), based on location, mode of formation and recent condition (Ageta, et al., 2000). Glacial lakes within the Hindu Kush Himalaya (HKH) are also classified into the erosion lake, valley trough lake, cirque lake, blocked lake, lateral and end-moraine lake and supraglacial lake (ICIMOD & UNEO 2001). The erosional lakes may include cirque and trough valley types which are more stable, while end moraine-dammed lakes are formed on the tongue of the glacier and are more susceptible to the event of GLOF. Supraglacial lakes are not regarded as an official glacial lake type by the world glacier inventory (WGI) as these are small in size and change position and size frequently on the glacier surface. However, the review of the events of GLOF reveals that some of the moraine dammed lakes that failed and caused a GLOF were derived from supraglacial lakes. The major category of the glacial lakes are ice-dammed pro-glacial lakes or moraine-dammed Lakes. Moraine dammed lake is an expression of glacier movement. These are the ones that are formed in the vicinity of retreating glaciers. During the Little Ice Age many glaciers in the Himalayas underwent rapid melting of their ice mass. Therefore, there was a decrease in the frontal extent of the glaciers leaving behind several boulders pebbles glacial tills collectively called as moraines. These moraine deposits form as a barrier or a dam like structure. Glacial melt water gets accumulated in the depression formed between these moraine dams and the glaciers at the frontal position of the glaciers. These moraine-dammed lakes can be between glacial and terminal moraine of a glacier or lateral and end moraine. Moraine-dam lakes are the results of the Little Ice Age, they are considered an unstable ones for being recent in origin. Moraine-dam lakes have the most devastating GLOFs impact as they are more susceptible. Even the slightest disturbances in the dam holding the lake water can lead to the sudden outburst. The availability of huge debris cover along with water, cause greater damage. Pictorial examples of glacial lakes defined by ICIMOD, 2011 are presented below.

**Plate 12: Tarn/cirque Lake of Dashaur on the Pir Panjal. Such lakes are almost permanent features on deglaciated terrains and have stability unless a catastrophic rockfall or slide debouches into it.**

**Plate 13: The Samudra Tapu Proglacial Lake. Increase in temperature and retreat of glacier would determine the future of such pro-glacial lakes. These types of lakes are extremely prone to flooding on account of increase in volume of water and resultant pressure.**

**Plate 14: Pro-glacial lake of Uldhampu glacier in the Miyar Basin. Such lakes have history of breaching and destroying farmland and bridges in the basin.**

**Plate 15: Avalanche blocked lake in front of Sonapani Glacier on the Great Himalayan Range. Such lakes are common in such mountain environments and have very short and non-disastrous impact.**

**Plate 16: Rock-glacier blocked Lake of Suraj Tal on the Great Himalayan Range. Such lakes are common and have prolonged yet non-disastrous effect as the water siphons through the boulders of the rock-glacier accumulate.**

**Plate 17: Mirror lake Chandra Tal formed due to the debris-flow blockage of supposed paleo-channel of the Chandra River behind a rock-bar. This lake has existed throughout the historical times.**

**Plate 18: Kettle and ribbon types of lakes in the glacial frontal area are common but purely transitory. This one in front of Miyar glacier (27 km) is one such example. These disappears on the seasonal and yearly time scale.**

**Plate 19: Moraine dammed lake in the glacial frontal environments. These have life-cycle normally on the decadal scale in this region.**

**Plate 20: Scenic Chandra Tal in June. Snow in the background supplies meltwaters through the debris-fans in the far background.**

**Plate 21: Melt water flows through the debris deposit from the slopes through mass movement. The Rock-bar and the Chandrabhaga 13 peak (CB 13) are in the background.**

**Plate 22: Suraj Tal at Baralacha (4800 m) during mid-May. Rock glacier in the far-left has been responsible for the formation of glacier and snow-melt waters around Baralacha on the Great Himalayan Range. The lake remains frozen for almost six months in a year.**

**Plate 23: End moraine and frost-shattered rocks create conditions for the melt-waters to accumulate and form lakes. Summer melt waters in the Neelkanth glacier environment.**

**Plate 24: Ablation Valley Lake of the Neelkanth in Thirot Watershed. The very formation between two lateral moraines have provided a fairly stable evolution of such lakes.**

**Plate 25: Ablation Valley Lake of the Menthosa Glacier. Water discharge point is visible in the Centre-left, with glacier descending from the higher peak. (Menthosa- 6400 m msl) in to the centre-background.**

**Plate 26: Supra-glacial lakes on the Neelkanth Glacier. Such temporary lakes have been observed to vanish through moulins into the subsurface areas seasonally.**

### *3.14.3 Glacial Lake Formations*

Formation of glacial lakes is multidimensional and multi-faceted. It is necessary to understand the process of formation of Glacial Lakes even before understanding outburst potential and consequent floods. The causes of Glacial Lake formation are (ICIMOD 2007):

#### 1. Geothermal Conditions

Glacier rich high altitude areas are the source regions for the formation of several large and small glacial lakes during the ablation period because of the presence of the several feeder glaciers. Geothermal and geomorphological conditions, coupled with global warming are the major factors responsible for the formation of glacial lakes, provided these are requisite conditions for blockade/accumulation to form such features.

#### 2. Global warming

In the ever-expanding industrialized world, warming caused by anthropogenic activities is supposed to be the main cause of accelerating glacier melts that increase volume of water in the associated lakes. In turn, a gradual increase in lake water increases the potential of an outbreak of the glacial lake. However, no studies have been carried out in the Indian Himalayas on such breaches due to the infrequent nature of occurrence in glacial lake outburst floods (GLOF). In addition, it is generally believed that a rise in atmospheric temperature happens due to regular emissions of carbon dioxide ($CO_2$) and other GHG gases that result in the 'greenhouse effect' in the atmosphere. Such '*GHE'* is considered to be the catalytic driver of the rapid melting of the glaciers and snow, thus causing lakes to grow and subsequently breach. Rapid industrialization in the developing countries in recent decades has now been associated with such increases in GHG emissions (IPCC, 2007).

### 3. Glacier retreat

A sequel to present global warming is the retreat of glaciers in many mountainous areas. During the 'Little Ice Age' (AD 1550-1850s), several glaciers grew much larger as compared to today. Large moraines formed in front of the glaciers as a result of this advance which have now got blocked by retreating glacier meltwaters, forming proglacial, supraglacial and moraine-dammed lakes. Glacial and inter-glacial are but natural cyclic processes that have happened many times in the past million years and even beyond. But the necessity of assessment of failures of these lakes and subsequent damages to the society and infrastructure demands immediate attention. On average, the Himalayas glaciers have receded by a kilometer since the termination of the Little Ice Age. This phase became a prominent factor that led to the formation of several new unstable glaciers in the vicinity of the waning glaciers particularly moraine-dam and pro-glacial lakes.

### 4. Increase of Glacial Lake Water Levels

Continuous increase in glacial lake water levels puts hydrostatic pressure on the moraine dams. When this hydrostatic pressure exceeds beyond the carrying capacity of the dams holding the lake waters, it leads to the dismantling of the dams. Thus, breaching point is an important parameters to look at. Some of the important causes that lead to an increase of the glacial lake water levels are as follows:

- Climatic fluctuations that is increased insolation due to any reason may cause rapid melting of glacier ice and snow with or without the retreat of a glacier.
- Persistent precipitation or increased snowmelt.

- Constriction of regular outlet because of re-adjustment of moraine boulders, misbalancing inflow because of blocking or obstruction of sub-surface flow or through the dams by deposition of sediments such as silt, sand.
- Thick layer of glacial ice (dead ice) weighed down by sediment below the lake bottom on re-settling of an iceberg which stops subsurface infiltration or seepage from the lake bottom;
- Shrinking of the glacier tongue higher up, causing melt water to accumulate within end moraine complex for increase in Proglacial Lake;
- Blocking of the lake outlet points by any advancing tributary glacier;
- Landslide at the inner part of the moraine wall, or from slopes above the lake;
- Falling off of the snow/ice avalanches within the lakes. This will not only generate waters and put a sheer stress on the dams eventually this will add more volume by the subsequent melting of the snow ass.
- Subterranean thermal activities (tectonics) causing melting of the glacial mass.
- En-glacial sub-surface flow of water between the nearby glacial lakes due to the difference of gradient.

## 3.15 GLACIER LAKE INVENTORY FOR LAHAUL & SPITI

Lahaul & Spiti drained by tributaries of Chenab, Chandra and Bhaga are a barren cold desert area rich in large glacier mass and a number of small and large glacial lakes. There are 63 glacial lakes identified in the district. It has the maximum number of glacial lakes in the state of Himachal Pradesh. These lakes are distributed invariably within the district across different valleys with different geographic dimensions. Details of all the lakes with respect to altitude, orientation, latitude and longitude is listed in the table.

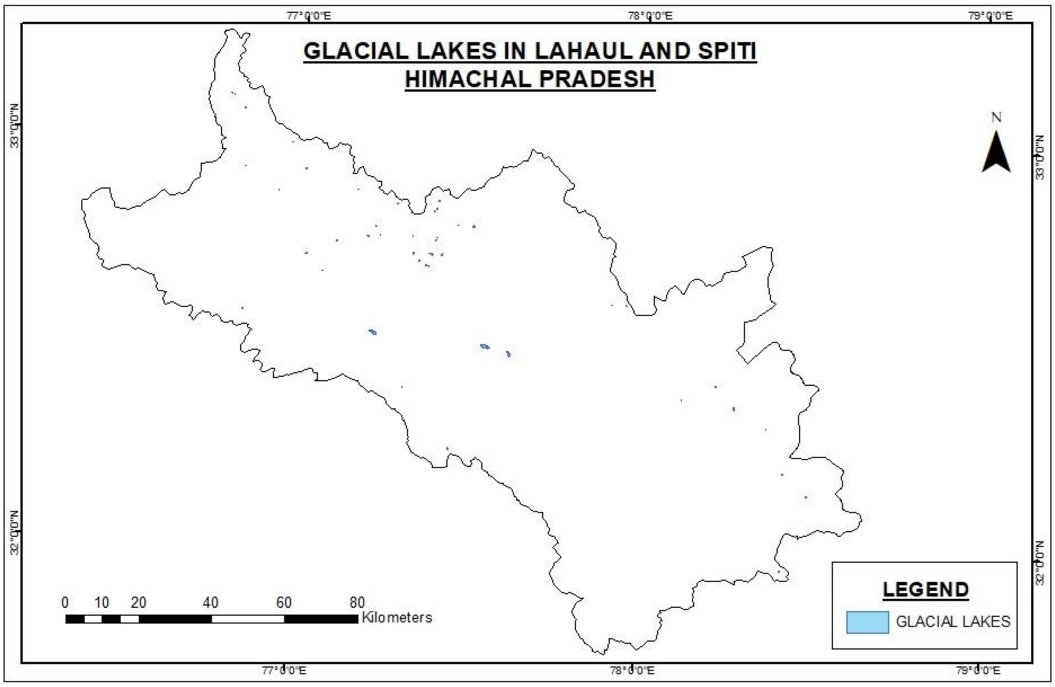



**Fig 3.8 Distribution of the Glacial Lakes in Lahaul & Spiti, 2020**

Moraine-dammed and pro-glacial lakes are the major glacial lake type in Lahaul & Spiti. Moraine-dam and pro-glacial lakes are formed at the snout or adjoining the source glaciers. These lakes are relatively recent in origin and formed at the snout of the glaciers during the Little Ice Age because of glacier retreat. These are called pro-glacial lakes. The frontal retreat of the glacier leads to the meltwater get accumulated in front of the parent glaciers within the depressions available. The cyclic and seasonal advance and retreat of the glaciers increase the volume of water in the lakes. Latent energy of the ice released further accelerates the melting rate, modifying the ambient thermal conditions. Therefore, the high rate of glacier movements, dynamism and availability of borders and debris material is responsible for maximum number of moraine-dammed and pro-glacial lakes. There are 17 moraine-dammed and 16 pro-glacial lakes and supra-glacial lakes each in Lahaul & Spiti. While there are only 2 valley glacial lakes and 11 blocked glacial lakes (Fig 3.11). If we look at the altitudinal distribution, most of the lakes are distributed between the altitude belts of 4000 to 5500 meters above mean sea level. This constitutes 50 percent share of the total lake type share. While only 3 percent of the glacial lakes are above the altitude of 5500 meters and 3 percent upto altitude zone of 4000 meters mean sea level (Fig.3.10). This strong juxtaposition is due to the relative topography of the mountains. At a very high and steep topography, glacial meltwater does not get a flat basin to form a depression or an impoundment. This restricts the accumulation of lake water and leads to the downward movement of water to the valley in the form of numerous seasonal streams. While at the lower altitude, higher run-off and frequent Kuhls also restrict the formation of glacial lakes. If we look at the areal extent or size of the glacial lakes, there is a gradual decrease in size of the glacial lakes with an increase in the elevation. There are 30 glacial lakes between the area of 0.05 to 0.01 $km^2$ comprising 47 percent of the total percentage of the lakes. There is only 1 lake with an area of 1 $km^2$. There are 10 glacial lakes in the range of 0.05 to 0.01 $km^2$ and 10 with less than 0.001 $km^2$ area Fig. 3.13). Decreasing size of glacial lakes with increasing altitude again exhibits the role of topography. Because higher the steepness and gradient, lower will be the deposition and accumulation of water.

| S.No | Area (in sq.km) | Mean Altitude above MSL (in meters) |
|---|---|---|
| Mean | 0.069731305 | 4915.058696 |
| Min | 0.001069399 | 2966 |
| Max | 1.353593785 | 5684.5 |
| Sum | 4.39307223 | |

**Table 3.8: Summarization of the Glacial Lake Inventory**

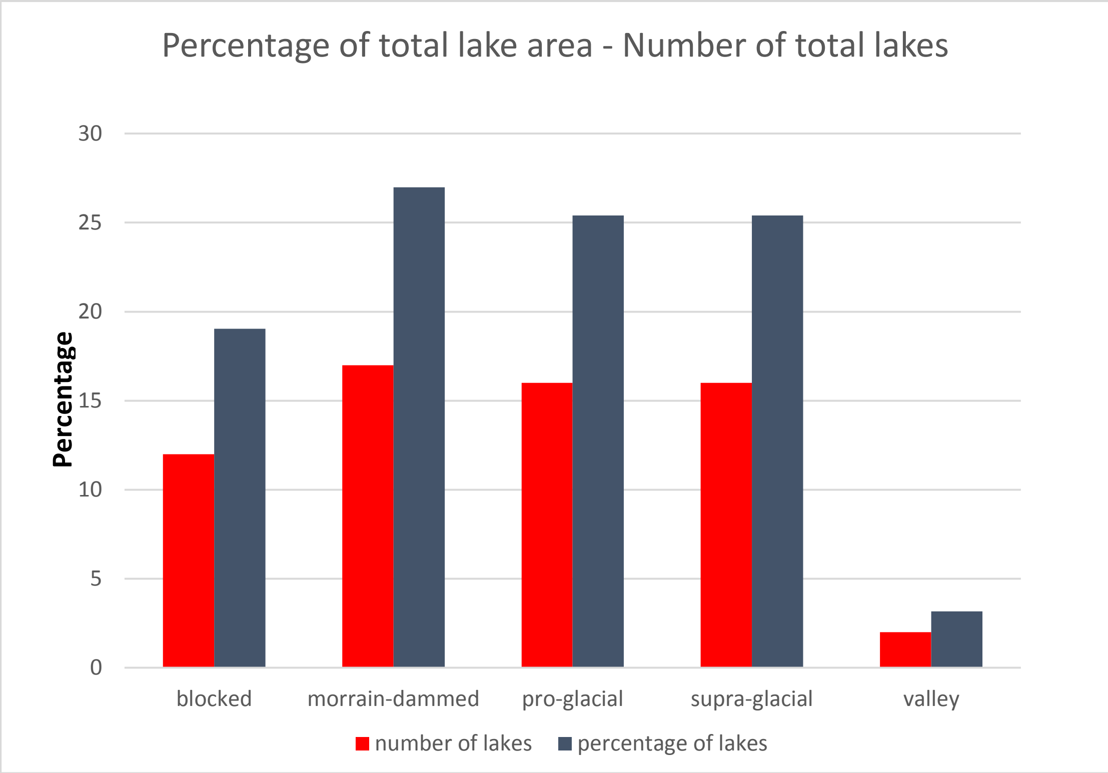



**Fig. 3.9 Type wise Distribution of glacial lakes in Lahaul & Spiti**

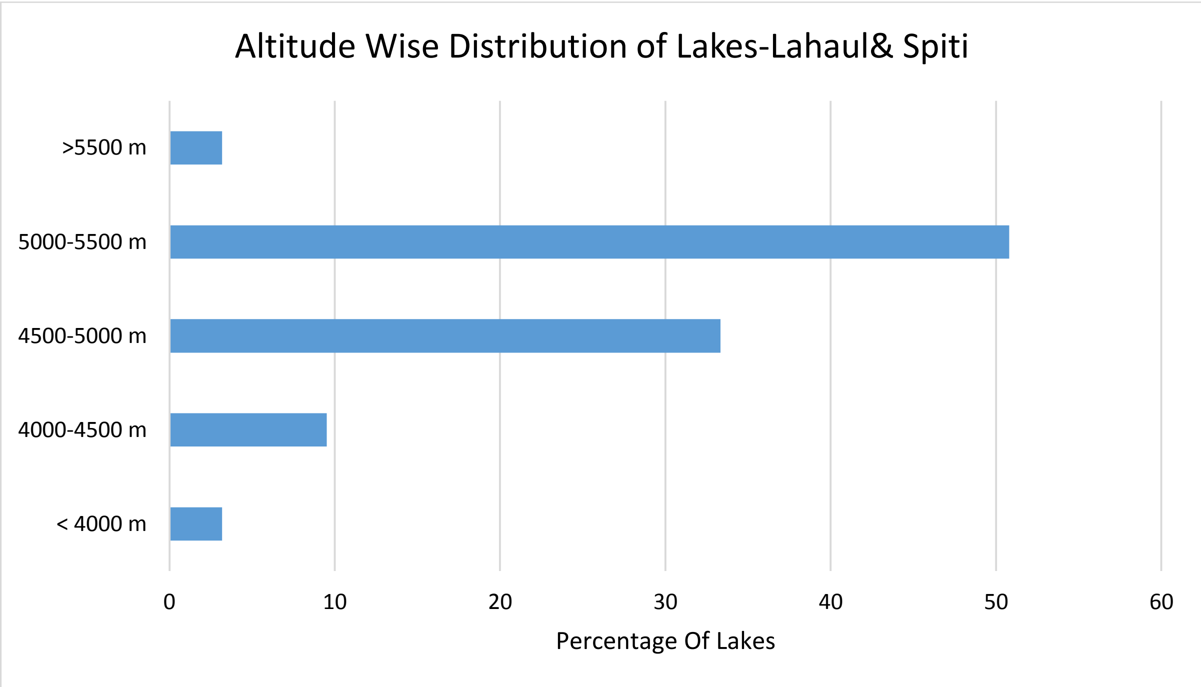



**Fig 3.10 Altitude Wise Distribution of the Glacial lakes in Lahaul & Spiti**

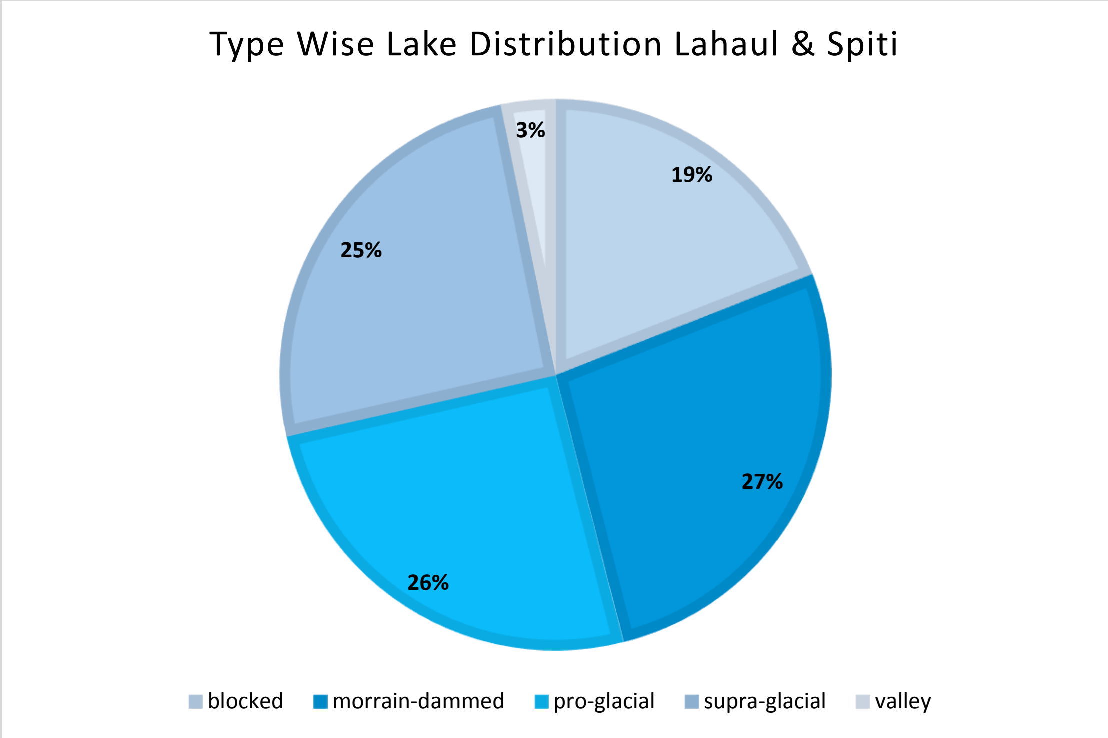



**Fig 3.11: Type Wise Distribution of the Glacial Lakes in Lahaul & Spiti**

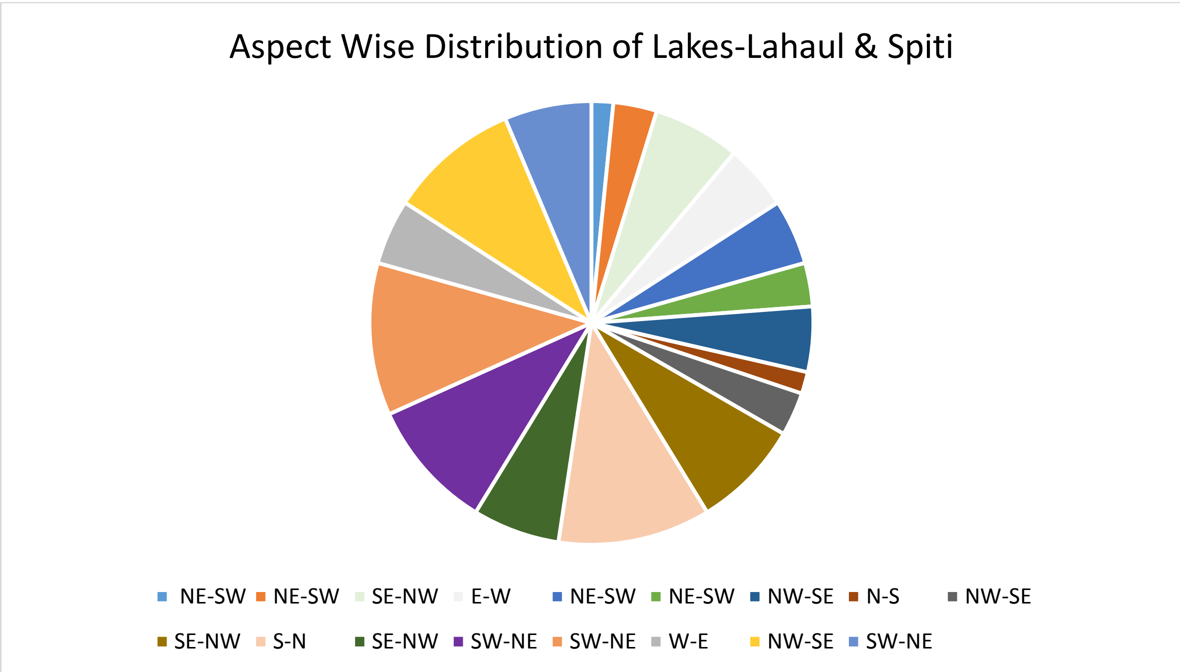



**Fig 3.12: Aspect Wise Distribution of the Glacial Lakes in Lahaul & Spiti**

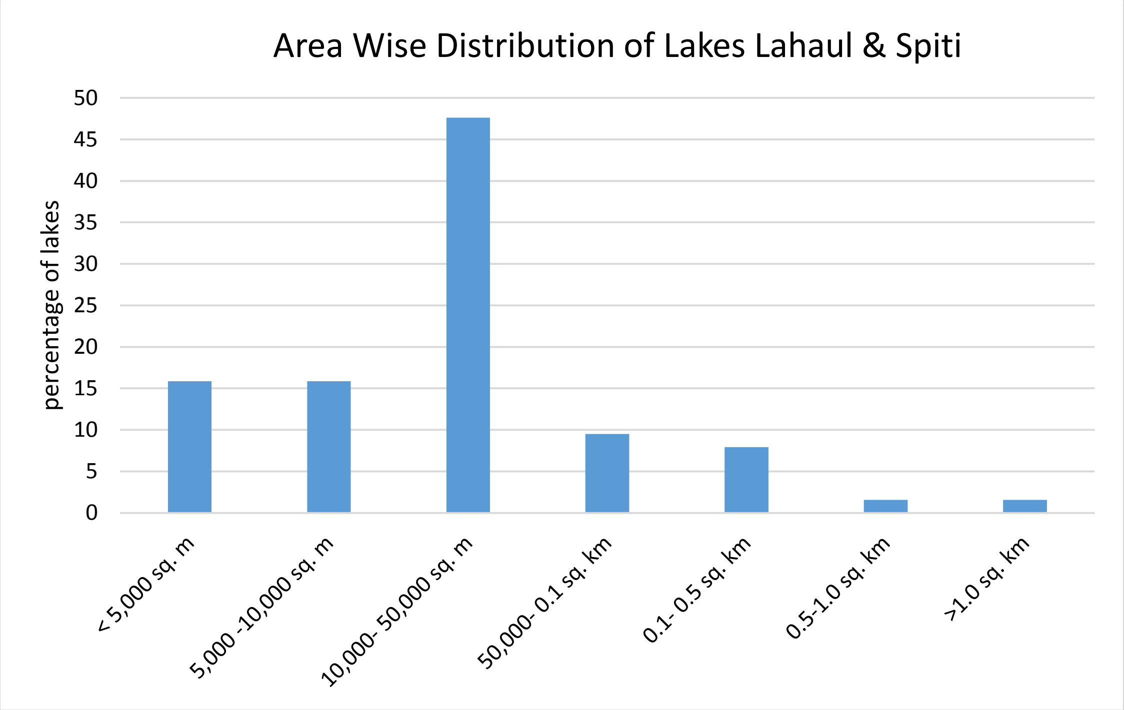



**Fig 3.13 Area Wise Distribution of the Glacial Lakes**

## 3.16 CONCLUSION

The Himalayan glaciers have shown heterogeneous irregular behavior. Therefore, there is an urgent need for continuous and long-term monitoring of various aspects of the Himalayan Cryosphere for the comprehensive understanding of glacial dynamics and their possible determent. The present study is based on various remotely sensed data, extensive Fieldwork, and morphometric analysis. Glacier dynamism is closely linked with the formation of lakes, their size and magnitude. At a larger perspective, the melting of glaciers leads to increase in the number and size of glacial lakes. Therefore, to understand the lake formation process and its various other parameters within the watershed, glacial dynamism is the keystone.

# CHAPTER 4

# ENVIRONMENT OF VULNERABLE GLACIAL LAKES

## 4.1 INTRODUCTION

Glacial lakes are an essential glacial-born landform that is associated with the dynamic nature of the glaciers and unstable and variable atmospheric conditions. They are an important feature in maintaining water budget in an area. These act as an important source of water for people in downstream valleys. Glacial lakes are a natural feature that may not always pose a threat to the surroundings causing floods. But other associated factors climatic, lithological, geological, tectonic anthropogenic and other such environmental factors make the lakes more vulnerable. Tarn lakes, valley lakes or lakes within old glacier tongue basin of retreating glaciers and other such old lakes are stable. While lakes formed between moraines with a steep slope of moraines, with slope angles exceeding beyond the internal friction value (threshold) of the moraine materials are vulnerable. Besides this, younger terminal moraines with narrow crests holding ice cores are vulnerable too (W. E. Grabs & J. Hanisch, 1993).

Along with the geomorphic and other such parameters of the lakes, lake surface temperature is also an important factor in lake dynamism. Lake surface temperature aggravates the melting of the glaciers further. Temperature has a cascading effect on lake reactions.Therefore.it is also imperative to analyze lake surface temperature within the watershed for further assessment. Land Surface Temperature (LST) is a useful proxy measure in data-scarce reaches of the mountainous environment. Several studies have validated the remotely sensed LST measurements made from TerraMODIS with in-situ AWS readings; represents strong correlation (Zhang, et al., 2014) (Crosman & Horel, 2009) (Wang, Wang, & Zhao, 2013) (Muskett, 2013) (Hall, et al., 2008). We have chosen to work with TerraMODIS satellite data because of its greater temporal span (February 2000 onwards). This data agrees with the glacier analysis years done in the earlier chapter. The overhead passage time of the TerraMODIS falls within two hours of local noon of the study area.

## 4.2 DATA SETS

1. Landsat images from https://earthexplorer.usgs.gov/

   a. Landsat 8 for 2020 were downloaded to the time period 21st September to 5th October and 20th March, 2020

   b. Landsat 5 images for 2010 were downloaded belonging to the time period 17th September to 26th September and 25th March, 2010. Images from 16th March, 2001 were also downloaded

   c. Landsat 7 images for 2000 were downloaded belonging to the time period 29th September to 8th October

   d. Landsat 1 MSS image for 1972 was downloaded for the date 4th September

2. Google Earth Pro imagery without cloud cover for each year

3. The Terra (EOS-AM1) and the Aqua (EOS-PM1) MODIS satellites were launched in December 1999 and May 2002, respectively, embedded with the MODIS payload. Both of the satellites effectively have the same specifications of 36 bands, although band 31 in Aqua MODIS saturates at temperatures about 60K below those for Terra (~400 K), in addition to a non-functional NIR band 6 (Hall, et al., 2008). MOD11B3 (procured from TerraMODIS), is a version 6 Level 3 LST product that exacts monthly average, per-pixel land surface temperature (LST) in a 1200 X 1200 (km) tile with a pixel size of 5600 meters (m). MOD11A2 (from Terra-MODIS) a version 6 Level 3 LST product, which is an eight-day composite data with a spatial resolution of 0.93 km has also been used to map the land surface temperature pattern. The temporal coverage of the data is from February 2000 till present. The 19 layered consolidated LST package is available from USGS Earth Explorer in the Hierarchical Data Format (HDF). ArcGIS 10.2.2 software has been used to operate on the LST Raster files. The overhead passage time of the TerraMODIS falls within two hours of local noon of the study area.

## 4.3 METHODOLOGY

1. All glaciers and lakes were digitized from Google Earth Pro for the Lahaul and Spiti district of Himachal Pradesh.

2. For comparison between Lake Boundary and an amount of permanent snow cover over three decades, Landsat 5, 7 and 8 images were used. The images were downloaded from https://earthexplorer.usgs.gov/. All the data, thus downloaded, belonged within a 20-day window to maintain consistency in the images and the dataset.

   a. For data from post-monsoon, before snowfall: For 2020, Landsat 8 images were downloaded belonging to 28$^{th}$ September, 2020. Similarly, Landsat 5 images for 2010 (17$^{th}$ September, 2010) and Landsat 5 images for 2001 (24$^{th}$ September, 2001) were downloaded.

   b. For data from pre-monsoon, post snowfall: For 2020, Landsat 8 images that were downloaded belonged to 20$^{th}$ March, 2020. Similarly, Landsat 5 images for 2010 (25$^{th}$ March, 2010) and Landsat 5 images for 2001 (16$^{th}$ March, 2001) were downloaded.

3. To estimate the change in glacier area and the permanent snow cover:

   a. Landsat FCC images were constructed for each decade and season. The glacial boundary was digitized manually using ERDAS IMAGINE 2014 and ARCGIS 10.5, respectively.

   b. The digitized boundaries for two seasons in a year were overlaid and using the swipe function in ArcGIS 10.5, permanent and seasonal snow cover was identified.

   c. The three sets of boundaries of the glaciers over the three decades were overlaid and the change in glacier area was identified. Thus, the quantity of glacial retreat was determined.

4. To estimate the change in the glacial lake boundary:

a. Landsat FCC images were constructed for each decade for the post-monsoon season i.e. September-October. The lake boundary was digitized manually using Erdas IMAGINE 2014 and ArcGIS 10.5, respectively.

b. The digitized boundaries for three decades were overlaid and using the swipe function in ArcGIS 10.5, permanent lake boundary and changed boundary was identified from 197-2001-2010 and 2010-2020.

5. The methodology includes the construction of a model using the Arc-GIS modeling function. An array of functions performed on the file add the extraction of sub-datasets, layers 1 & 5 titled Day and Night Land Surface Temperature. Focused segments are in the 16-bit integer format with a scaling factor of 0.2. The values have a valid range of 7500-65535, and the unit of data representation is in Kelvin. MOD11B3 monthly composite data comes with Sinusoidal inherent projection, which later has been defined according to the suitability of the description of the study area. The LST raster files have been re-projected twice as Himachal Pradesh is positioned within World UTM Zone 43 N. Area of interest has been extracted by masking from the base raster in consonance with the selected watersheds. To find the average monthly LST of the concerned watershed, the pixel values within the confines of the watershed shape-file needed to be differentiated from the ones situated outside of it. After masking the images, Raster to ASCII function has been used for each of the images to convert the raster values within the bounds of the watershed into ASCII format. Python 2.7 Software has been used to iterate on the ASCII values to calculate an average LST for the concerned watershed. The effective calibrating formula for the SDS (scientific data sets) for rescaling the individual DN values is: DN * 0.02, giving a value in the range of 1501310.7 K. The respective Day and Night time DN values are individually iterated to find the Monthly Average LST of the watershed in Kelvin scale for the respective case. The day and night-time values are averaged out to find the Mean Monthly LST. The unit of representation has been changed to degrees Celsius values to be used in the current study as per the international standard metric system.

6. The data thus obtained has been dealt with in estimating the mean annual LST in the selected basins of Himachal Pradesh. The range of temperature has been studied in concerned basins. Temperature pattern has been noted in successive accumulation (October-March) and ablation periods (April- September), respectively. The mean monthly LST in the major basins of Himachal Pradesh has also been estimated. Within the boundaries of Himachal Pradesh, mean monthly land surface temperature (°C) has been extracted for Beas, Chenab, Ravi, Satluj, Tsarap Chhu and Yamuna constitute the major basins within the state for land surface temperature analysis. The land surface temperature has been visually represented using the processed raster files and extracting point values to interpolate the degree Celsius isolines within the boundaries of individual basins. The iso-lines present the land surface temperature characteristics for both Day and Night in the individual basin. Common values for isolines have been assigned for a comprehensive understanding of the land surface temperature pattern over a period of 19 years.

7. The mean annual LST has been calculated to understand the basic pattern of land surface temperature in the selected basins of the concerned states. Although the basin average annual land surface temperature estimation is done based on the area covered, it roughly builds up an understanding of the temperature regime over the selected time span of 18 years. Surprisingly, certain years reflect a general trend of raised temperatures while others reflects a general trend of lower temperatures, which more or less corresponds to all the basin average LST in the selected basins of both the Himalayan states.

Out of 63 lakes in Lahaul & Spiti some are temporary and some permanent that might never cause floods. But few could be hazardous. That’s why identification and analysis of such vulnerable lakes are important followed by detailed field investigations and regular monitoring along with the dynamism of their parent glaciers. Thus, a detailed study of the overall micro- environment of glacial lakes is extremely environment. In this context, further rapid spatio-temporal changes or extreme dynamism of glacial lakes in terms its area and volume change is an important parameter to look at besides analyzing the land surface temperature (LST) therein.

The present study depicts the change in the lake area from 1972 to 2020 of the Sissu and Samudra Tapu glacial lake and overall analysis of LST for Chenab watershed within which the *potentially dangerous glacial lakes (PDGL's)* fall in the region. The increasing rate of glacial lakes along with an areal extent and their potential flood volumes is one of the most important indicator of potential outburst hazards. This can enhance the magnitude of hazard.

In the present study, two lakes have been selected for further study based on parameters given below (W. E. Grabs & J. Hanisch, 1993).

1. Area of a lake above 0.5 km sq.
2. Type of lake
3. Lakes attached or are near to the parent glaciers or at the snout of the glaciers.
4. Large volume of the lakes.

## 4.4 RESULTS

### *4.4.1 The Chenab Basin*

The Chenab or Chandrabhaga basin (within Himachal Pradesh) covers the Lahaul & Spiti and Chamba districts of Himachal Pradesh. The Chenab emerges out of the confluence of two major streams, namely, Chandra, originating from Baralacha Pass (8700 meters AMSL) and Bhaga, from Suraj Tal in the proximity of Baralacha La. These rivers confluence at Tandi at 3000 m AMSL. Countless rivers and rivulets from the vast basin spread over the largest district of Himachal Pradesh. It is oriented in an east to west direction, and major portions of the river basin shy away from the direct influence of the Indian Summer Monsoon; rather, the climate is determined by the interaction of the landscape with the Westerlies as well as a little of the ISM. The LST pattern here is notably varied due to the orographic gradient. July and August are the months which exhibits the highest basin average LST, whereas January and February are the coldest months of the year. The highest basin average LST in the summer months was noticed in July 2013 with a value of 10.64°C ± 0.53°C followed by August 2005 with a value of 9.76°C ± 0.49°C and August 2014 with a value of 9.62°C ± 0.48°C. Lowest summer temperatures were exhibited in August 2010 with a value of 6.57°C ± 0.33°C. The coldest basin average LST in the winter months was noticed in January 2008 with a value of -19.95°C ± 1.00°C, followed by January 2011 and 2012 with values -18.99°C ± 0.95°C and 18.67°C ± 0.93°C respectively. January 2005 also reflected low winter temperature at -18.66°C ± 0.93°C. Years 2000, 2001 exhibited warm winter basin average LST values at -16.30°C ± 0.81°C and -16.25°C ± 0.81°C, respectively. The year 2016 has also experienced a warm winter with the basin average LST value of -16.21°C ± 0.81°C (Fig. 4.1).

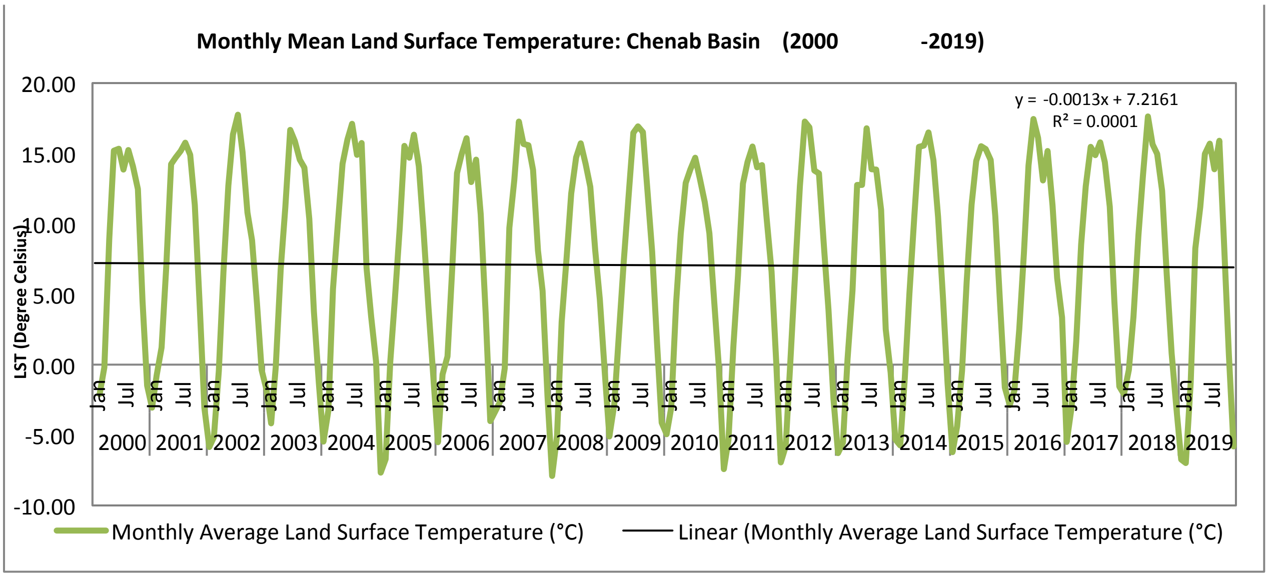



**Fig.4.1. The Linear Trend of Mean Monthly LST for the Chenab basin (2000-2017).**

#### *4.4.1.1 Accumulation period*

The highest basin average LST noticed in the 18 year periods was in the accumulation period of the year 2016-17 with a value of -7.94°C ± 0.4°C. The accumulation period undoubtedly reflected the highest ever accumulation period basin average LST in the years of the probe. This value is followed by -9.60°C ± 0.48°C in the accumulation period of 2000-01. Other years which reflected high basin average LST were 2002-03 and 2003-04 with values -9.78°C ± 0.49°C and 9.83°C ± 0.49°C respectively. The lowest basin average LST was noticed in the accumulation periods of 2004-05 and 2001-02 and 2004-05 with values -11.62°C ± 0.58°C and -12.36°C ± 0.62°C respectively. Other years with low basin average LST in the accumulation periods were 2009-10 and 2012-13 with values -11.63°C ± 0.58 and -11.18°C ± 0.56°C respectively. The tend-line shows a positive increase with an $R^2$ value of 0.04 over a span of 19 years (Fig 4.2).

Visual comparison from the maps yields the following observations. The years 2001, 2004, 2008, and 2016 were undoubtedly the warmest accumulation period seen by the Chenab basin in the 18-year period. Whereas, 2000, 2003, 2005, 2006, and 2014 reflected colder LST conditions in the Chenab Basin, according to the maps prepared for the study (Fig. 4.2).

| Year | Average LST in Accumulation Months (°C) |
|---|---|
| **2000-01** | -9.59 ± 0.47 |
| **2001-02** | -11.61 ± 0.58 |
| **2002-03** | -9.78 ± 0.48 |
| **2003-04** | -9.83 ± 0.49 |
| **2004-05** | -12.36 ± 0.61 |
| **2005-06** | -9.85 ± 0.49 |
| **2006-07** | -10.64 ± 0.53 |
| **2007-08** | -10.98 ± 0.54 |
| **2008-09** | -10.63 ± 0.53 |
| **2009-10** | -11.63 ± 0.58 |
| **2010-11** | -10.71 ± 0..53 |
| **2011-12** | -10.55 ± 0.52 |
| **2012-13** | -11.17 ± 0.55 |
| **2013-14** | -10.70 ± 0.53 |
| **2014-15** | -10.28 ± 0.51 |
| **2015-16** | -10.40 ± 0.52 |
| **2016-17** | -7.94 ± 0.39 |
| **2017-18** | -8.84 ± 0.45 |
| **2018-19** | -14.33 ± 0.96 |

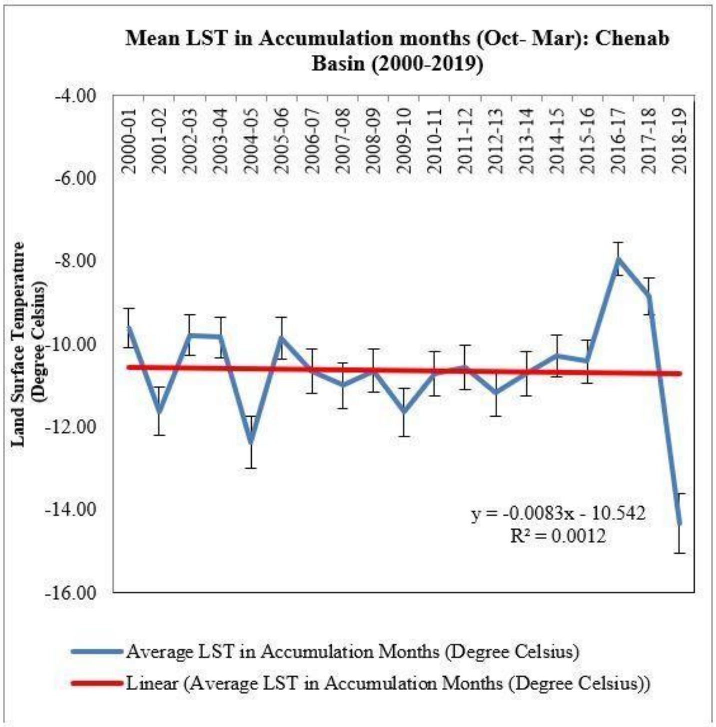



**Fig.4.2. Linear Regression of Accumulation Months' LST in the Chenab basin.**

From the data created over a time-span of 18 years, it can easily be concluded that the years 2001, 2004, 2008, and 2016 reflect the highest LST in the Chenab basin. Years 2000, 2002, 2003, 2005, 2006, and 2014 have reflected lower night-time LST in the Chenab basin (Fig. 4.2, Fig 4.3).

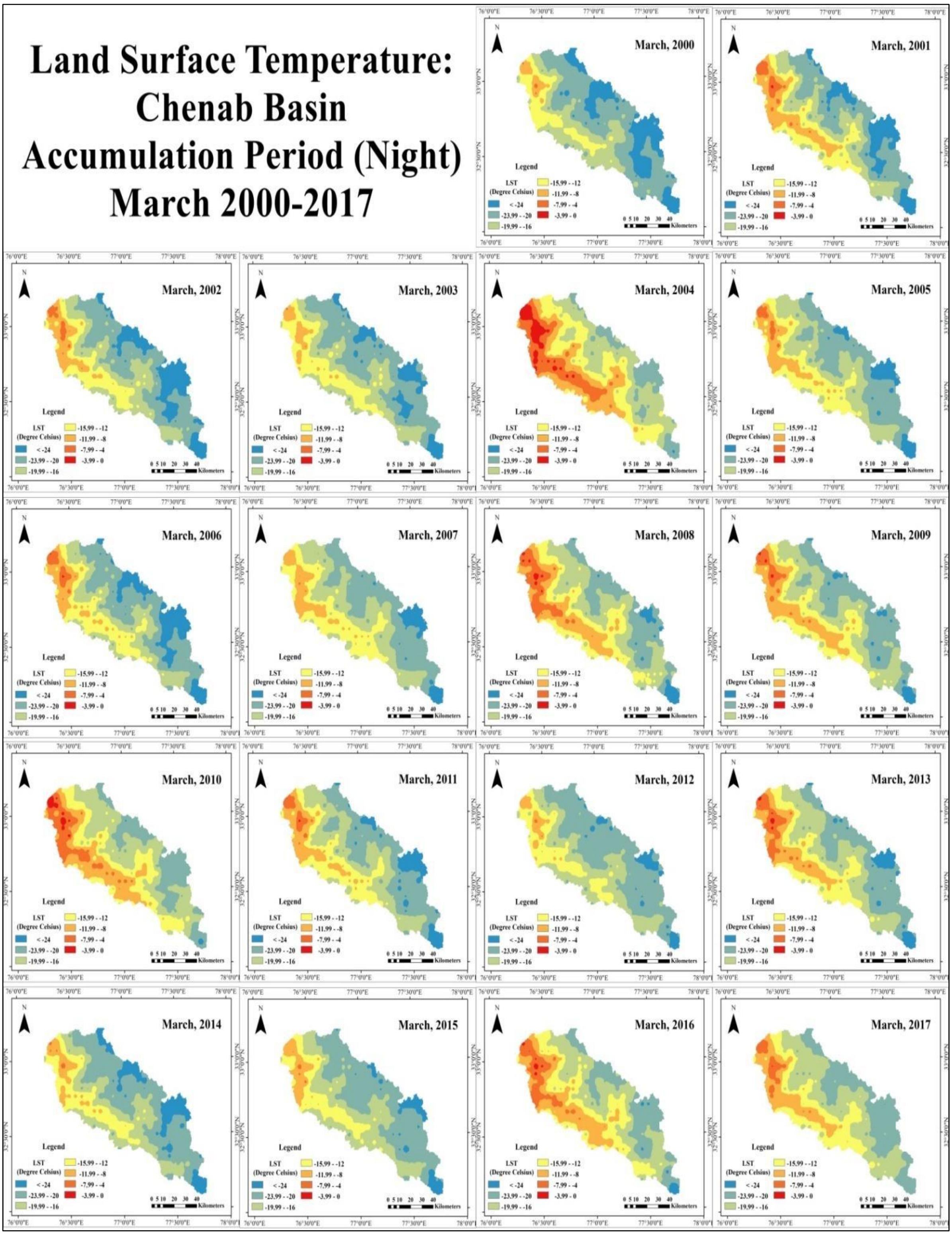



**Fig.4.3. LST distribution (Night Time) for the month of March of the Chenab basin in Himachal Pradesh (2000-2017).**

*4.4.1.2 Ablation period*

The months of April through September of every year are considered to be the standard ablation period in the mountainous environment of the Himalayan region. These months reflect the highest average temperatures experienced by the basin. From the available dataset, ablation period temperatures have been calculated for a period of 18 years. The ablation period is characterized by the melting of seasonal snow precipitated on the landscape in the accumulation months (Oct-Marr). Agrarian economic activities are, therefore, limited only to this period in the study area.

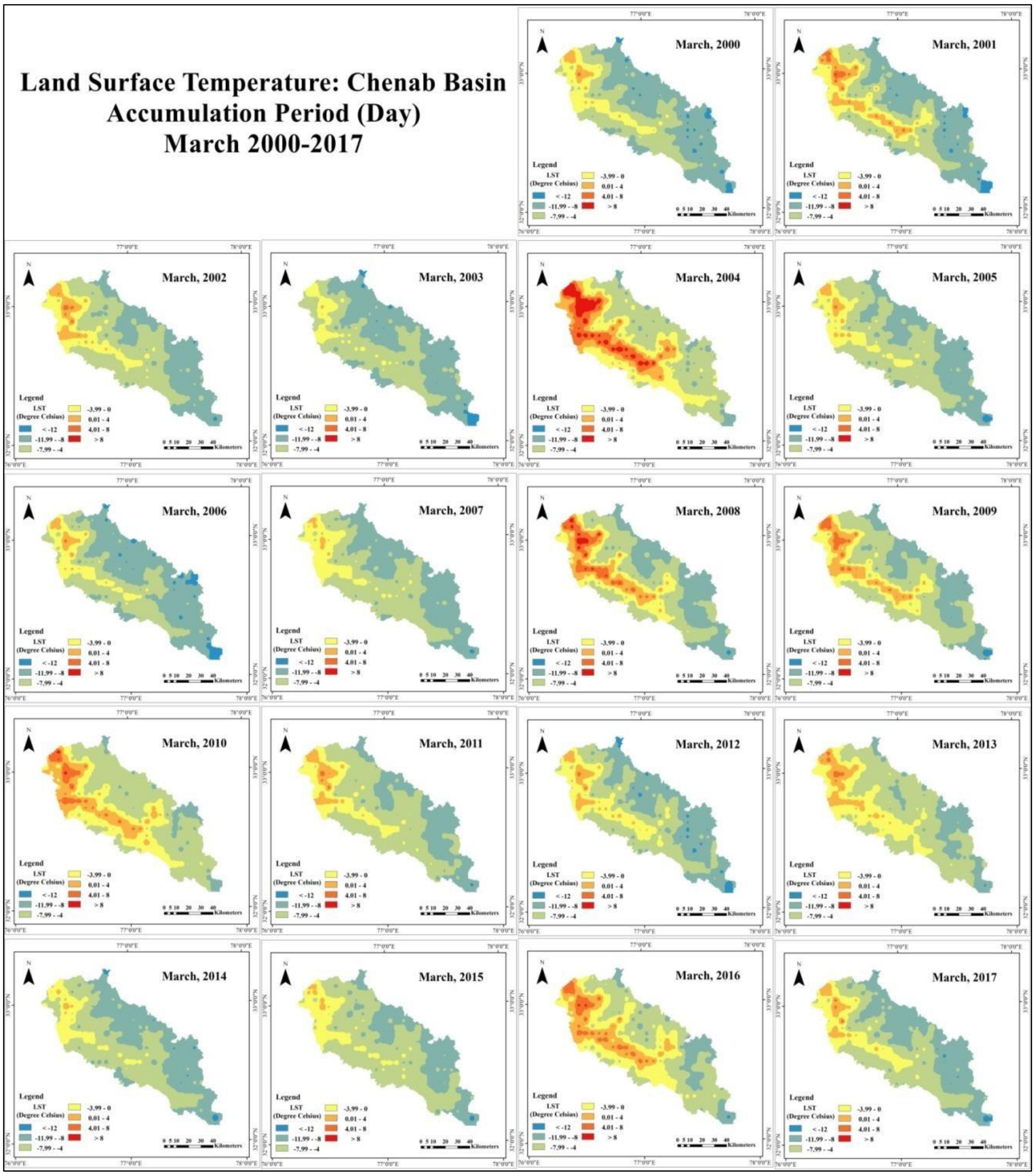



**Fig. 4.4. LST Distribution (Day Time) for the Month of March of the Chenab Basin in Himachal Pradesh (2000-2017).**

The Highest basin average ablation period temperatures were observed in the years 2007 and 2004 with values 5.53°C ± 0.28°C and 5.29°C ± 0.26°C respectively. Other years which also exhibited high LST values in the concerned basin were 2000, 2001 and 2016 with values 4.77°C ± 0.24°C, 4.75°C ± 0.24°C, and 4.74°C ± 0.24°C respectively. The lowest ablation period basin average LST was reflected in the year 2010 with a value of 2.36°C ± 0.12°C, closely followed by 2005 and 2012 with values 2.79°C ± 0.14 and 2.97°C ± 0.15 respectively. The liner trend-line shows a negative change in the ablation period LST with an $R^2$ value of 0.07, which indicated progressively cooler summers in the basin (Fig.4.5).

| Year | Average LST in Ablation Months (°C) |
|---|---|
| **2000** | 4.76 ± 0.23 |
| **2001** | 4.75 ± 0.23 |
| **2002** | 3.49 ± 0.17 |
| **2003** | 3.60 ± 0.18 |
| **2004** | 5.29 ± 0.26 |
| **2005** | 2.79 ± 0.13 |
| **2006** | 3.89 ± 0.19 |
| **2007** | 5.52 ± 0.27 |
| **2008** | 4.00 ± 0.20 |
| **2009** | 3.04 ± 0.15 |
| **2010** | 2.35 ± 0.11 |
| **2011** | 3.80 ± 0.19 |
| **2012** | 2.96 ± 0.14 |
| **2013** | 3.08 ± 0.15 |
| **2014** | 3.24 ± 0.16 |
| **2015** | 3.51 ± 0.17 |
| **2016** | 4.11 ± 0.21 |
| **2017** | 4.22 ± 0.21 |
| **2018** | 4.11 ± 0.21 |
| **2019** | 3.16 ± 0.16 |

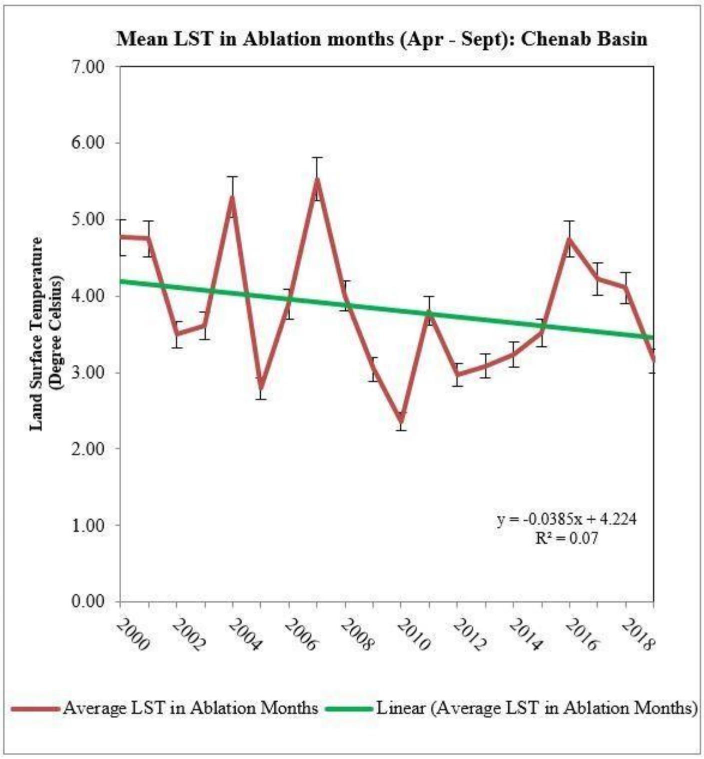



**Fig.4.5. Linear Regression for Ablation Months' LST in Chenab basin (2000-2019).**

It is clear from the analyzed data that the years 2000, 2001, 2004, 2006, 2007 and 2016 were undoubtedly the warmest summers in the Chenab Basin. On the contrary 2002, 2003, 2005, 2009, 2010, 2012 were observed to be the years which shows comparatively lower temperatures in the Chenab basin during the Ablation Period. Figure 28 correctly represents the calculated basin average values for the summer months (Fig.4.7).

Data for the years 2000, 2001, 2004, 2007, 2013, 2016, and 2017 show higher LST values as extracted from the Night scenes upon the Chenab basin in the ablation period. Whereas, 2002, 2005, 2008, 2009, 2010 and 2012 were low years for night-time ablation period LST on an aerial coverage (Fig. 4.6).

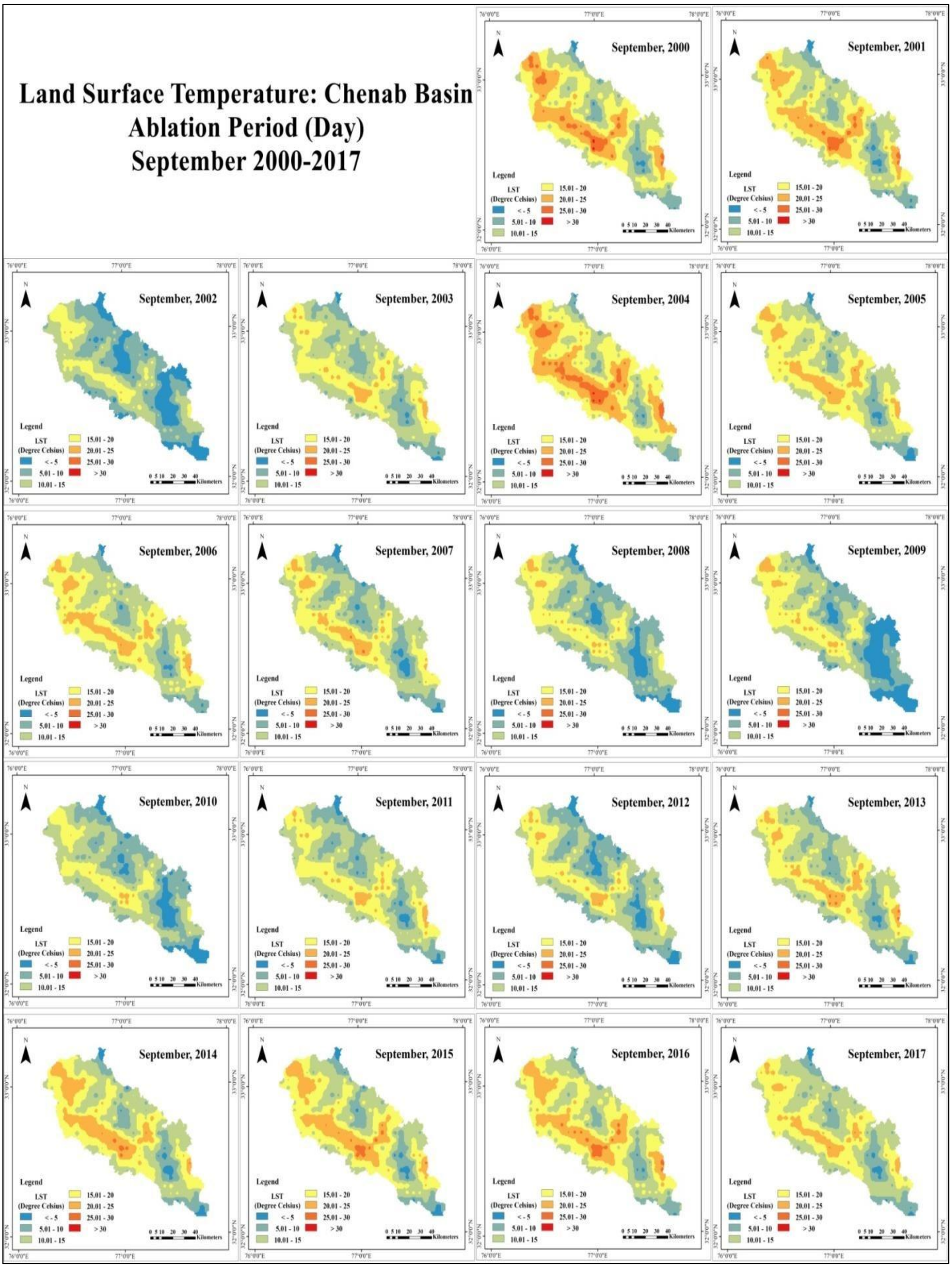



**Fig.4.6. LST Distribution (Day Time) for the Month of September of the Chenab Basin in Himachal Pradesh (2000-2017).**

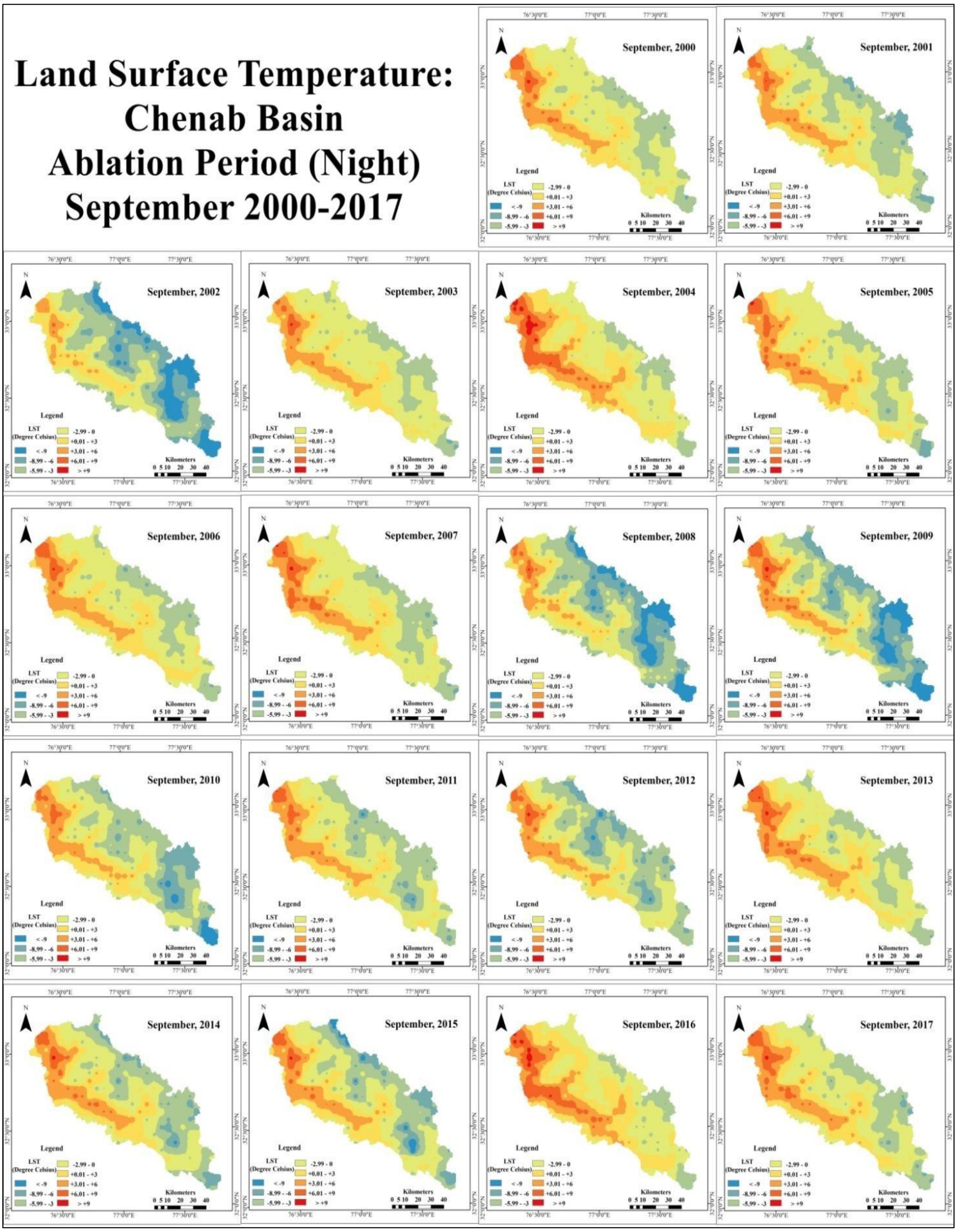



**Fig.4.7. LST distribution (Night Time) for the Month of September of the Chenab Basin in Himachal Pradesh (2000-2017).**

### *4.4.2. Equilibrium Line Altitude within Chenab Basin*

Chenab Basin houses the maximum number of large glaciers (exceeding 10 km$^2$) while the largest in the basin include the Bara Shigri and the Samudra Tapu glaciers. The ratio for the estimation of ELA has been taken as 0.48. The maximum average Equilibrium Line Altitude in the glaciers in the year 2000 was noted to be 5576 m while the lowest was noted at 4641 m AMSL respectively. In the year 2016, the highest estimated ELA was noted at 5541 m and the lowest at 4663 m AMSL. The median value of change in ELA is 0 which means that most of the bigger glaciers in the valley are stable according to their mass balance. However, the maximum retreat value of 22 meters has been observed for glacier with ID CH538 which has shown a retreat of 0.38 km$^2$ (Table 4.1). The second highest value of ELA retreat has been shown by CH604 where the area reduction has been nil.

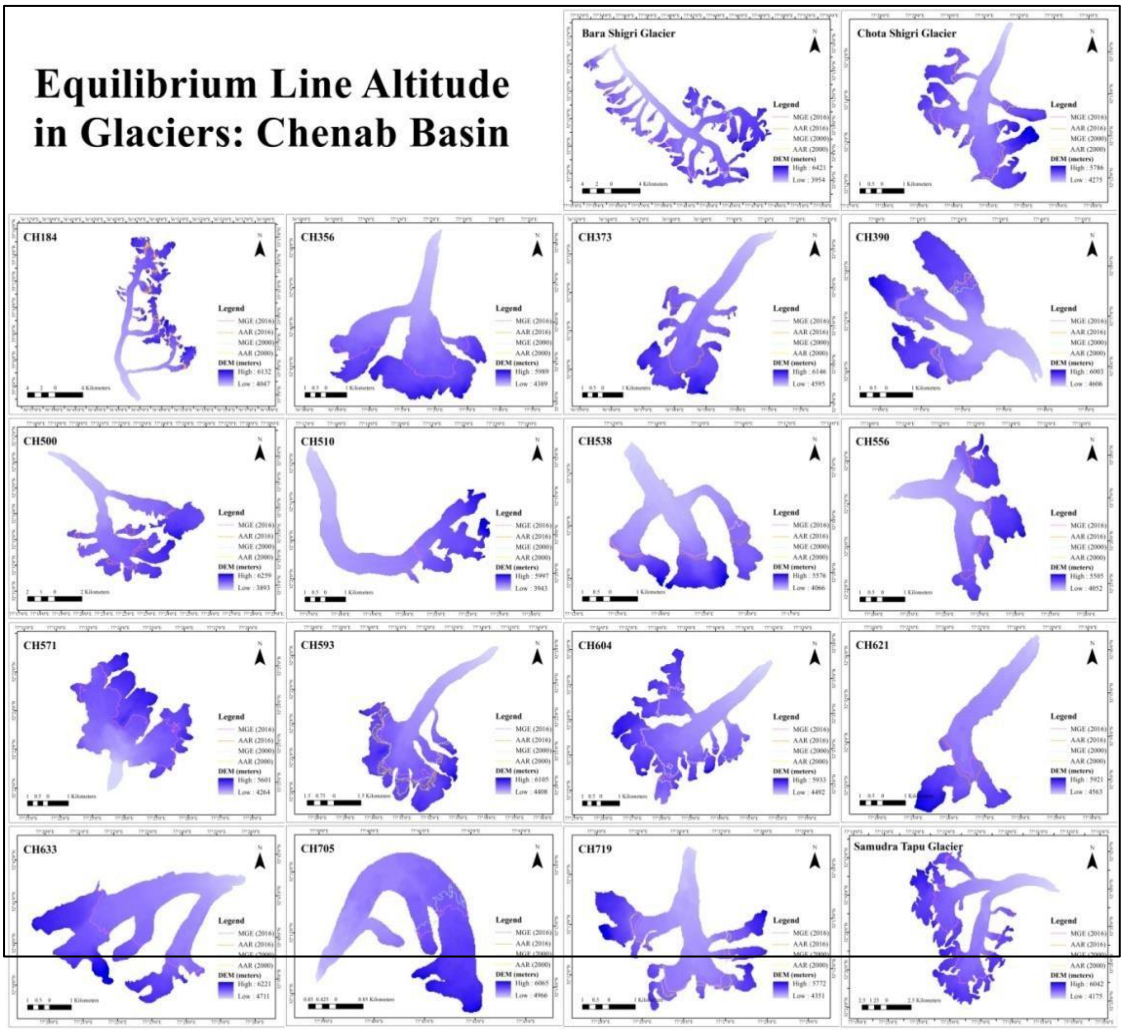



**Fig. 4.8 ELA in Glaciers: Chenab Basin.**

| Name | Equilibrium Line Altitude (MGE in meters) 2000 | Equilibrium Line Altitude (AAR in meters) 2000 | Average Equilibrium Line Altitude (meters) 2000 | Equilibrium Line Altitude (MGE in meters) 2016 | Equilibrium Line Altitude (AAR in meters) 2016 | Average Equilibrium Line Altitude (meters) 2016 | Change in ELA 2000 2016 | Glacier Area ($Km^2$) 2000 | Glacier Area ($Km^2$) 2016 | Change in glacial area ($Km^2$) 2000 2016 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Bara_ Shigri** | 5379 | 5379 | 5379 | 5359 | 5359 | 5359 | 20 | 102.80 | 99.83 | 2.97 |
| **CH184** | 5304 | 5304 | 5304 | 5272 | 5322 | 5297 | 7 | 73.79 | 73.68 | 0.11 |
| **CH356** | 5314 | 5314 | 5314 | 5314 | 5314 | 5314 | 0 | 21.13 | 21.13 | 0.00 |
| **CH373** | 5420 | 5420 | 5420 | 5420 | 5420 | 5420 | 0 | 14.92 | 14.92 | 0.00 |
| **CH390** | 5331 | 5381 | 5356 | 5362 | 5362 | 5362 | -6 | 13.19 | 13.21 | -0.02 |
| **CH500** | 5268 | 5318 | 5293 | 5268 | 5318 | 5293 | 0 | 30.55 | 30.55 | 0.00 |
| **CH510** | 4668 | 4668 | 4668 | 4668 | 4668 | 4668 | 0 | 15.19 | 15.19 | 0.00 |
| **CH538** | 4641 | 4641 | 4641 | 4638 | 4688 | 4663 | -22 | 10.91 | 10.53 | 0.38 |
| **CH556** | 4827 | 4877 | 4852 | 4827 | 4877 | 4852 | 0 | 11.97 | 11.97 | 0.00 |
| **CH571** | 5189 | 5189 | 5189 | 5189 | 5189 | 5189 | 0 | 18.97 | 18.97 | 0.00 |
| **CH593** | 5433 | 5483 | 5458 | 5401 | 5451 | 5426 | 32 | 17.27 | 17.06 | 0.21 |
| **CH604** | 5317 | 5317 | 5317 | 5334 | 5334 | 5334 | -17 | 20.90 | 20.90 | 0.00 |
| **CH621** | 5138 | 5188 | 5163 | 5138 | 5188 | 5163 | 0 | 10.92 | 10.92 | 0.00 |
| **CH633** | 5286 | 5286 | 5286 | 5286 | 5286 | 5286 | 0 | 21.95 | 21.95 | 0.00 |
| **CH705** | 5576 | 5576 | 5576 | 5541 | 5541 | 5541 | 35 | 10.72 | 10.72 | 0.00 |
| **CH719** | 4876 | 4926 | 4901 | 4876 | 4876 | 4876 | 25 | 12.06 | 12.06 | 0.00 |
| **Chota_ Shigri** | 5100 | 5100 | 5100 | 5050 | 5100 | 5075 | 25 | 12.15 | 12.15 | 0.00 |
| **Samudra_ Tap u** | 5300 | 5300 | 5300 | 5300 | 5300 | 5300 | 0 | 75.39 | 75.06 | -0.33 |

**Table 4.1. Equilibrium Line Altitude (ELA) Characteristics of Selected Glaciers in the Chenab Basin.**

Considerable numbers of glaciers in the Chenab basin have shown no changes in their area (Figure 4.8). Most of the bigger glaciers in the valley reflect considerable glacier cover. Such an example is reflected by glacier ID CH510; 80 percent of the glacier area is covered by debris, while the change in area is zero and the change in ELA is also zero. Therefore, the glacier can largely be understood as a balanced glacier over the period of 17 years, notwithstanding local and seasonal changes in the ELA. The maximum advancement in the glacier ELA has been seen in the glacier CH705 with a change of 35 meters over a period of 17 years (2000-2016). The largest glacier in the basin Bara Shigri with an area change of 2.97 km$^2$ shows a recession of 20 meters in 2000-2016; Samudra Tapu glacier reflected no change in ELA, while a gain of 0.33 km$^2$ in the glacier area was noticed during a brief time span.

The Chenab basin reflects a cyclic pattern of SCA through the 17 years of probe (Figure 4.9 & 4.10). While the higher Snow Cover Area values in the basin often reach 100 % of the basin area, the summer season reflects a permanent snow cover of 15-20 %. The annual SCA observes knocks and falls depending upon the season. There is a steep rise in the snow cover after the monsoon season in the months of late September and October. There exist evidences of partial spring melting which is generally again rejuvenated. Monthly snow cover area is derived from the 8-day snow cover maps by taking an average of each month for 17 years (Figure 4.10). Upon computing monthly data, it has been observed that during the winter months (October- April) 50-100% area of the total basin area is covered by snow. Particularly the months of January- April record the highest snow cover in the year, where nearly 90-100% area of total basin is covered by snow. SCA remains approximately at 50% by precipitation and low temperatures.

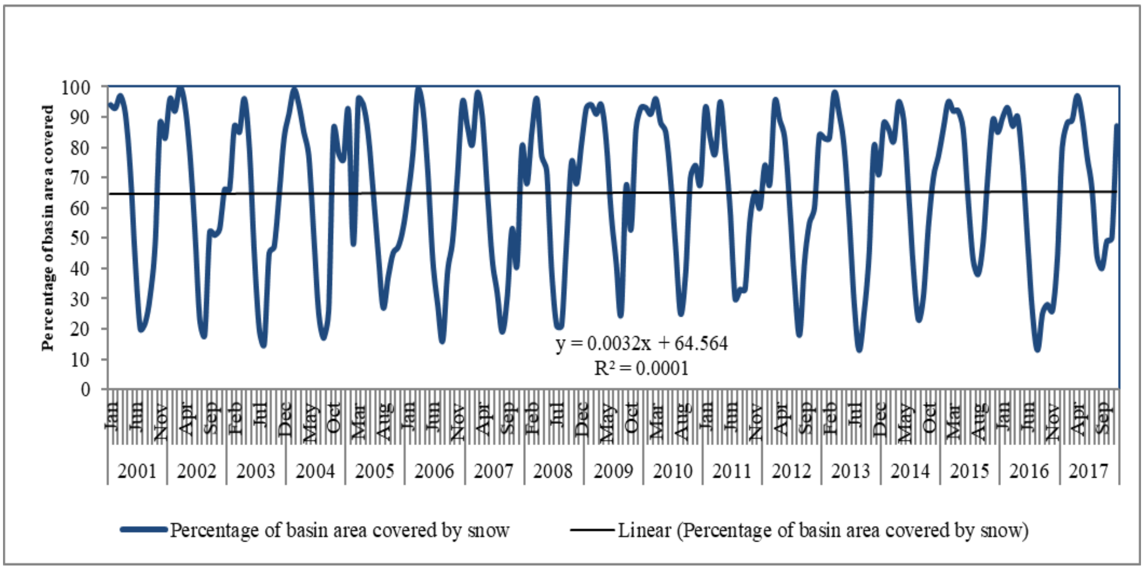



**Fig 4.9. Percentage of Basin Area Covered by Snow in Chenab Basin (2001-2017).**

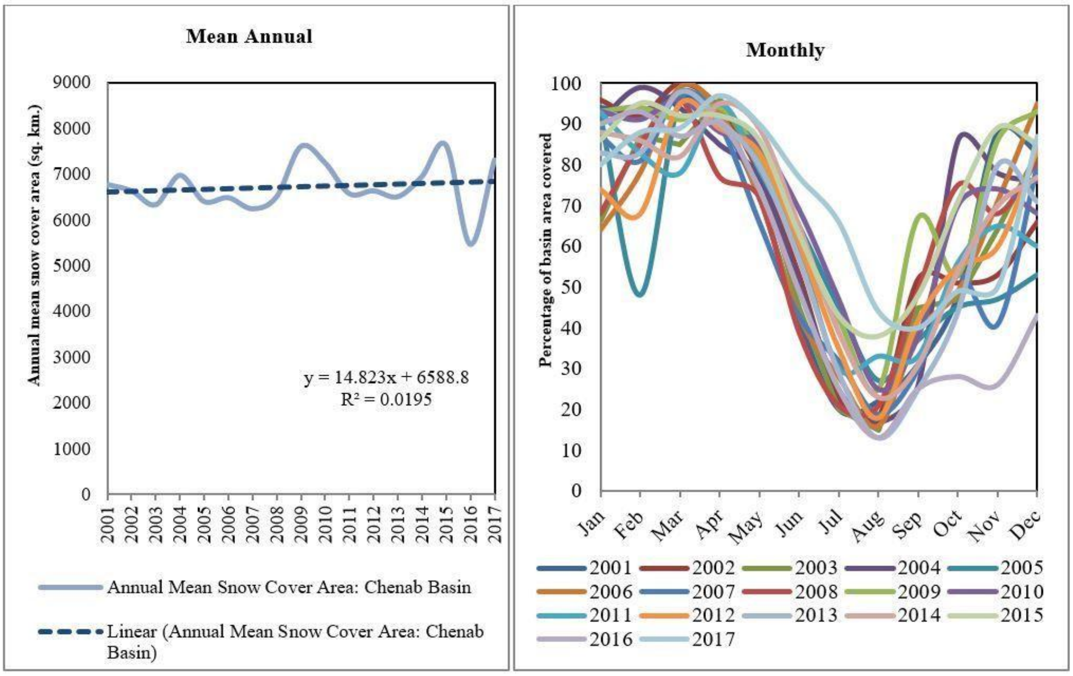



**Figure 4.10. Temporal (Annual/Monthly) Snow Cover Areas in Chenab Basin, 2001-2017.**

The inter-annual mean values of Snow-Covered Area have been extracted from 8 days composite SCA product provided by MODIS for Chenab Basin. The years 2015, 2017, 2009 and 2010 recorded SCA more than 7000 $km^2$ with peak values of 7631.79 $km^2$, 7310.28 $km^2$, 7603.34 $km^2$ and 7247.51 $km^2$ respectively, while the whole basin area is 10366.3 $km^2$. The lowest SCA is noted in the year 2016 5465.79 $km^2$, which is almost half of the total basin area. The remaining years present a more or less constant SCA with very little variations ranging between 6242.71 $km^2$ and 6973.31 $km^2$. The trend line bears an $R^2$ value of 0.0195 with a slope of 14.82 with the intercept placed at 6588 $km^2$; indicating a mildly positive inclination, or increase in the snow cover in 2001-2017 of the basin area by the beginning of June and then starts steadily declining till the beginning of October. In the summer months SCA never goes below 13% represented by permanently covered mountain caps and glaciers. Most of the years experienced 45-75% SCA during summer months. It indicates that most of the area of Chandrabhaga basin remains snow covered throughout the year except for the months of July and August. The accumulation period observes cyclic pattern of SCA while the lower values of SCA was observed in the years 2003, 2006, 2008, 2012 and 2017 respectively (and Figure 4.11). El Nino does not impart any effect on the mid-latitude westerlies which brings in moisture from the Caspian and the Adriatic in the Accumulation period; like it is reflected in the El Nino year of 2016. High SCA values in the Accumulation period in the Chenab Basin was noticed in the years 2002, 2010 and 2016 respectively. These years may be said to have had an intense mid-latitude westerly induced precipitation in the form of snow.

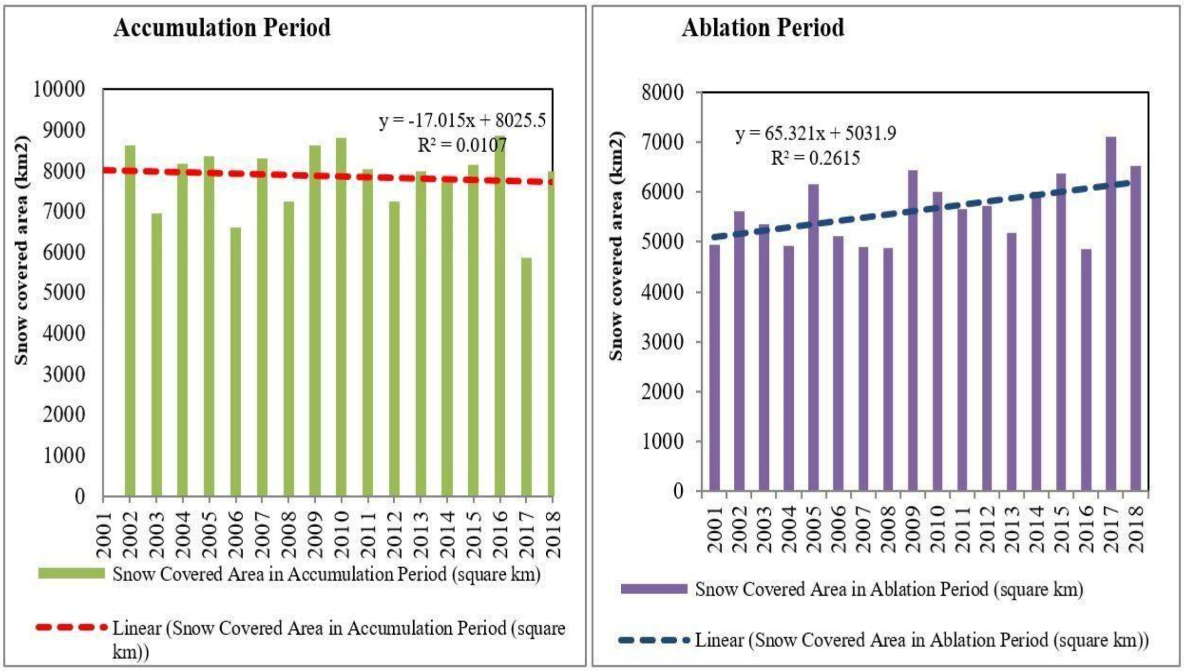



**Fig 4.11. Seasonal (Accumulation/Ablation Period) Snow Cover Area in Chenab basin, 2001-2018.**

The pattern of accumulation in Chandrabhaga basin shows that it initiates from the end of September and reaches to cover 80-90% of the basin till April, while the month of May also reflect considerable snow cover usually amounting to more than 70% of the total basin area. The trend line of accumulation period SCA indicates an insignificant decrease with $R^2$=0.01. Ablation mainly occurs during June to August. Ablation values of each year are varied cyclically within a maximum 7107.59 km² in 2017 to minimum 4857.63 km² in 2004. The trend line of ablation period mean SCA presents a mildly positive trend with an $R^2$ value of 0.19 indicating increase in mean ablation period snow cover statistically.

| Years | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **2001** | 94 | 93 | 97 | 91 | 72 | 42 | 20 | 22 | 31 | 48 | 88 | 83 |
| **2002** | 96 | 92 | 100 | 94 | 78 | 53 | 23 | 18 | 52 | 51 | 53 | 66 |
| **2003** | 66 | 87 | 85 | 96 | 80 | 45 | 20 | 15 | 45 | 47 | 64 | 83 |
| **2004** | 91 | 99 | 94 | 85 | 77 | 51 | 25 | 17 | 26 | 86 | 78 | 76 |
| **2005** | 92 | 48 | 96 | 94 | 84 | 65 | 45 | 27 | 37 | 45 | 47 | 53 |
| **2006** | 64 | 78 | 99 | 93 | 72 | 43 | 28 | 16 | 39 | 49 | 71 | 95 |
| **2007** | 87 | 81 | 98 | 90 | 66 | 43 | 32 | 19 | 30 | 53 | 41 | 80 |
| **2008** | 68 | 85 | 96 | 77 | 72 | 39 | 21 | 21 | 49 | 75 | 68 | 81 |
| **2009** | 93 | 94 | 91 | 94 | 82 | 58 | 42 | 25 | 67 | 53 | 86 | 93 |
| **2010** | 93 | 91 | 96 | 88 | 85 | 69 | 47 | 25 | 38 | 70 | 74 | 68 |
| **2011** | 93 | 83 | 78 | 95 | 79 | 59 | 30 | 33 | 33 | 56 | 65 | 60 |
| **2012** | 74 | 68 | 95 | 89 | 83 | 61 | 35 | 18 | 42 | 55 | 60 | 84 |
| **2013** | 83 | 83 | 98 | 91 | 80 | 57 | 29 | 13 | 25 | 44 | 80 | 71 |
| **2014** | 88 | 86 | 82 | 95 | 89 | 65 | 39 | 23 | 31 | 54 | 70 | 77 |
| **2015** | 86 | 95 | 92 | 92 | 86 | 63 | 43 | 38 | 48 | 71 | 89 | 85 |
| **2016** | 90 | 93 | 87 | 90 | 74 | 49 | 25 | 13 | 25 | 28 | 26 | 43 |
| **2017** | 80 | 88 | 89 | 97 | 90 | 77 | 66 | 44 | 40 | 49 | 50 | 87 |
| **2018** | 92 | 91 | 94 | 95 | 85 | 60 | 48 | 35 | 53 | 90 | | |

**Table 4.2. Percentage of Monthly Snow Cover Area in Chenab basin, 2001-2018**

## 4.3 SPATIO-TEMPORAL CHANGES IN THE GLACIAL LAKES

In terms of the vulnerable lakes within the Chenab basin, two lakes have been selected for further detailed study. These lakes are Sissu Lake and Samudra Tapu glacial lake. Sissu lake is located at lat/long 32° 29´8083 N and 77° 33´4443 E and an elevation of 4200 m AMSL near the snout of the glacier while Samudra Tapu is at 77.54654285 E and 4156.650179 N. The present study has mapped and analyzed Sissu and Samudra Tapu lakes and their parent glaciers from 1972 to the period of 2001, 2010 and 2020. In the year 1972, total glacier area of Sissu was 27.991 $km^2$ .In 2001, it deceased up to 25.7 $km^2$ and the change rate was -8.18477. While in 2010, the glaciers depicted a slight increase of 1.245% and increased up to 26.02 $km^2$. Decadal decrease rate of glaciers from 2010 to 2020 is abnormally high at a rate of -10.914 $km^2$ and reduced up to 23.18 $km^2$. As per the law of conservation of energy, change and decrease in glacier and seasonal snow cover add on to the increase in lake area and volume. Sissu lake area that was 0.199 $km^2$ in 1972 increased to 0.46 $km^2$ in 2001 and 0.59 $km^2$ in 2010 with the increase rate of 131.155%(within a span of 29 years) and 2.260% respectively. In the year 2020 from 2010, at a rate of 57.62% lake area increased to 0.93 $km^2$. In case of the Samudra tapu watershed, glacier area decreased to 88.9 $km^2$ from 91.34 $km^2$ from 1972 to 2001(within span of 28 years).From 2001 to 2010 there is again an increase in the glacier area similar to Sissu watershed. While from 2010 to 2020 there is a sharp reduction in glacier area to 68.64 $km^2$ with decadal decrease rate of -14.33653%. Samudra tapu glacial lake area was 0.3 $km^2$ in the year 1072 which increased to 0.71 $km^2$ in 2001, 0.98 $km^2$ in 2010 and presently is 1.39 $km^2$ in 2020.This peculiar increase in glacier area in both the watersheds in 2010 could be because of the high rate of snowfall in the particular. This is supported by the heavy seasonal snowfall in the year as there is increase in the extent of seasonal snow cover in the region. Decadal change rate and present status of both the watershed is present below in the table 4.3.

| Sissu Watershed | | | | | | |
|---|---|---|---|---|---|---|
| Year | Lake Area(.$km^2$) | Seasonal Snow Cover ($km^2$) | Glacier Area ($km^2$.) | % Change in Lake Area | % Change in Seasonal Snow Cover | % Change in Glacier Area |
| 1972 | 0.17 | 10.58 | 27.99 | | | |
| 2001 | 0.46 | 16.68 | 25.70 | 131.15 | 57.65 | -8.18 |
| 2010 | 0.59 | 24.04 | 26.02 | 28.26 | 44.12 | 1.24 |
| 2020 | 0.93 | 13.36 | 23.18 | 57.62 | -44.42 | -10.09 |

**Table 4.3 Temporal Change in the Sissu Glacial Lake**

| Samudra Tapu Watershed | | | | | | |
|---|---|---|---|---|---|---|
| Year | Lake Area | Seasonal Snow Cover | Glacier area | % Change in Lake Area | % Change in Seasonal Snow Cover | % Change in Glacier Area |
| 1972 | 0.3 | | 91.34 | | | |
| 2001 | 0.72 | 71.42 | 88.9 | 4.34 | -28.58 | -2.44 |
| 2010 | 0.98 | 86.67 | 75.39 | 36.11 | 16.48 | 4.35 |
| 2020 | 1.39 | 68.64 | 75.00 | 41.83 | -31.36 | -14.33 |

**Table 4.4 Temporal Change in Samudra Tapu Glacial Lake**

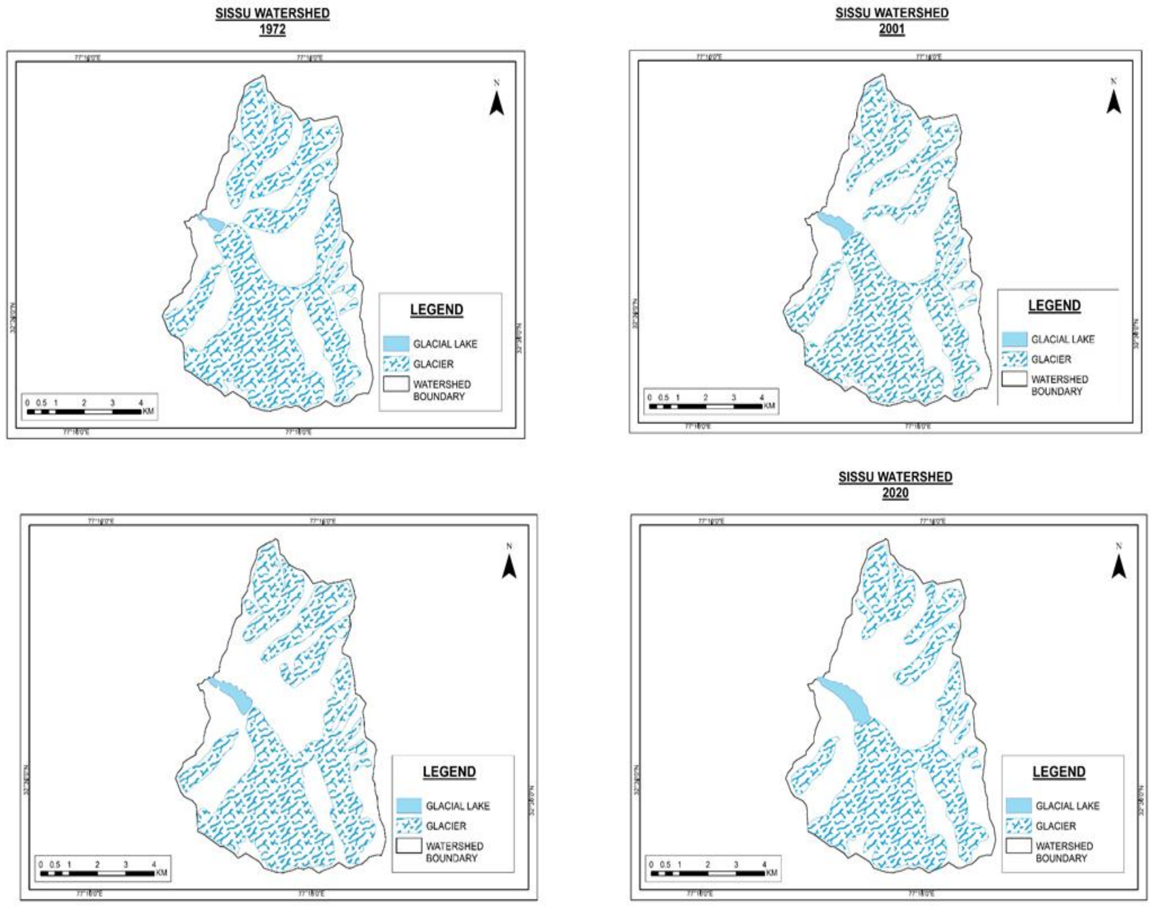



**Fig 4.12 Spatial Extent of Sissu Glacial Lake With Respect to Change in Area of Source Glaciers**

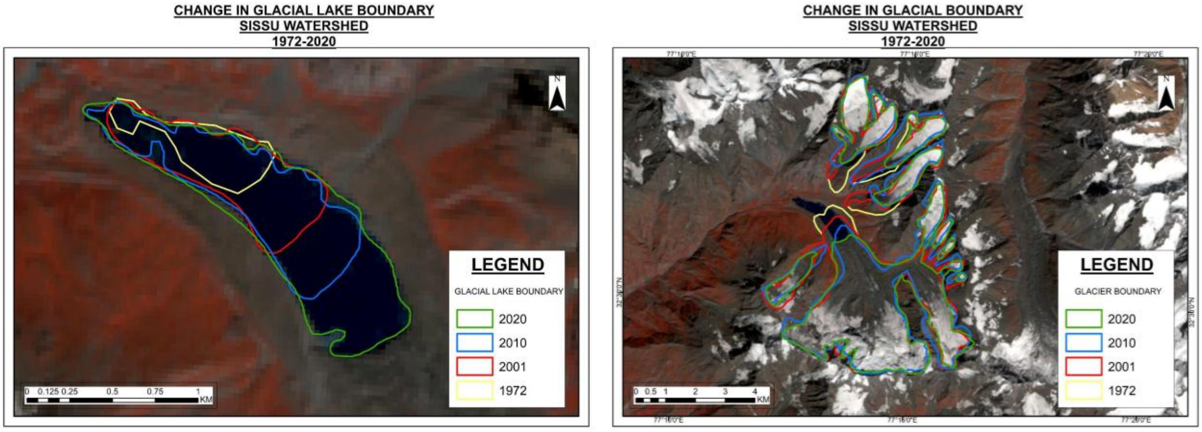



**Fig 4.13 Satellite Image showing an Areal change in extent of glaciers (a) and change in Lake Area for four decades (b)**

**Plate 27: Field photographs of Sissu Lake showing its pro-glacial nature and feeder stream that is Sissu nalah**

**Fig 4.14 Google Earth Image of Pro-Glacial Sissu Lake depicting Freeboard of the Moraine dam**

The bathymetry map of the Sissu also shows the deepening of the lake. The lake is deeper towards the source glaciers. This will lead to more accumulation of the water in the lakes from the source glacier. Figure 4.13 also supports this fact. The lake is getting bigger and deeper at the same time. From the period of 1972, due to backwards movement of the lake towards the source depth has increased. This marks the area which was an active zone of glacial activity. Due to the melting and recession of the glaciers, the exposed deep area has now become an extended part of the lake. Thereby, increasing the depth and area of the Sissu Lake.

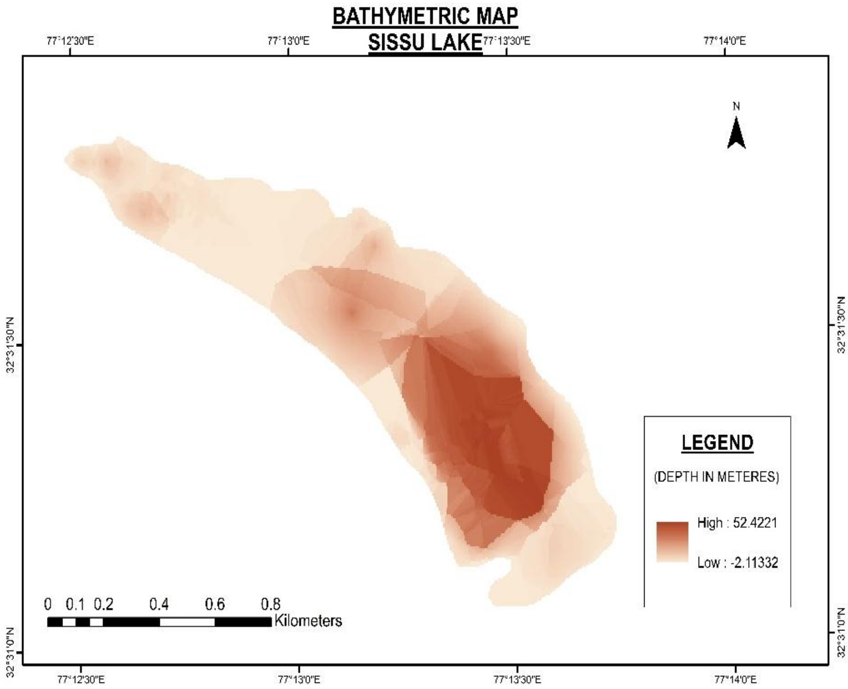



**Fig 4.15 Depth of the Sissu Glacial Lake**

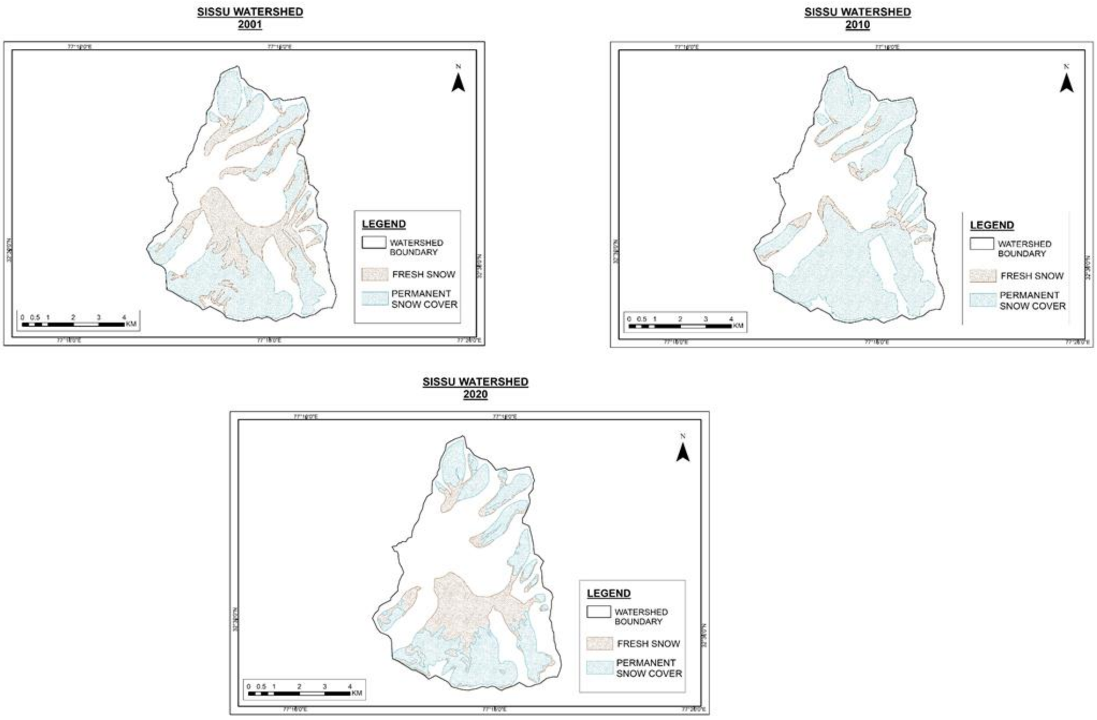



**Fig 4.16 Seasonal and Permanent snow cover distribution in Sissu watershed**

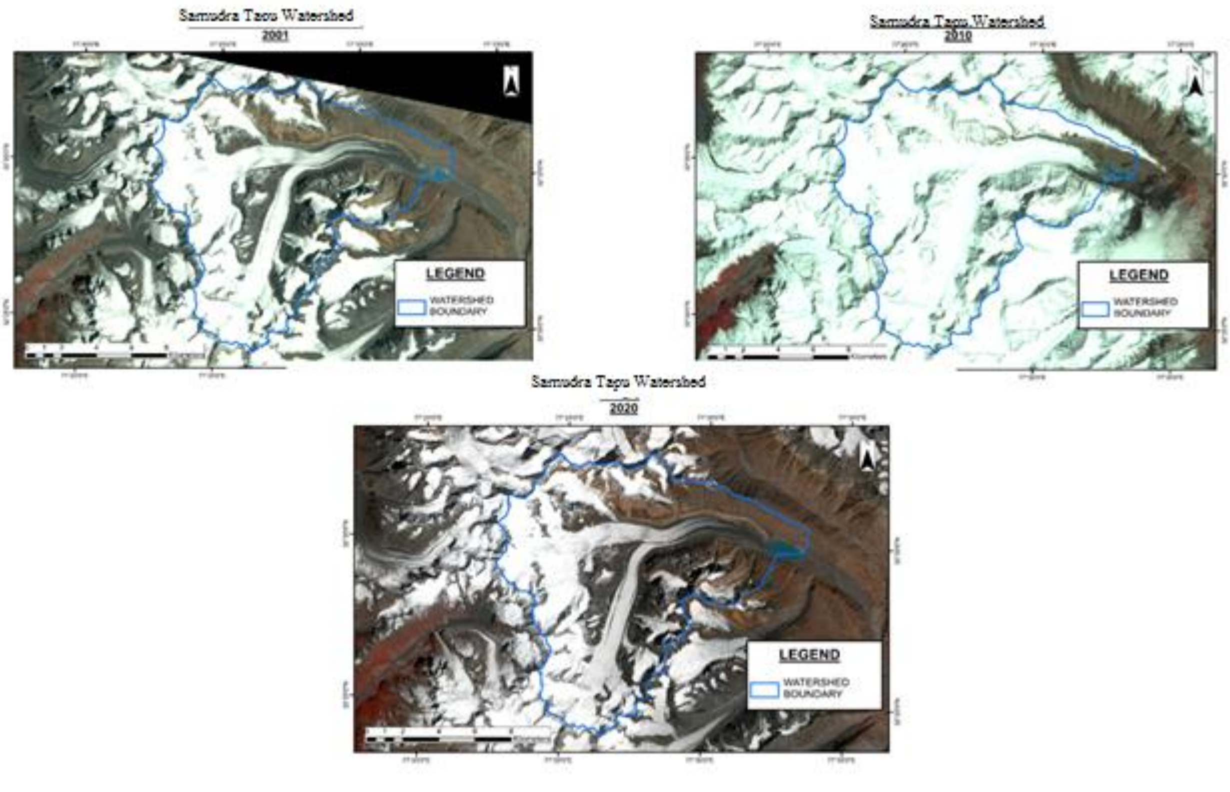



**Fig 4.17 Change in glacier extent in the year 2001(a) 2010(b) 2020(c)**

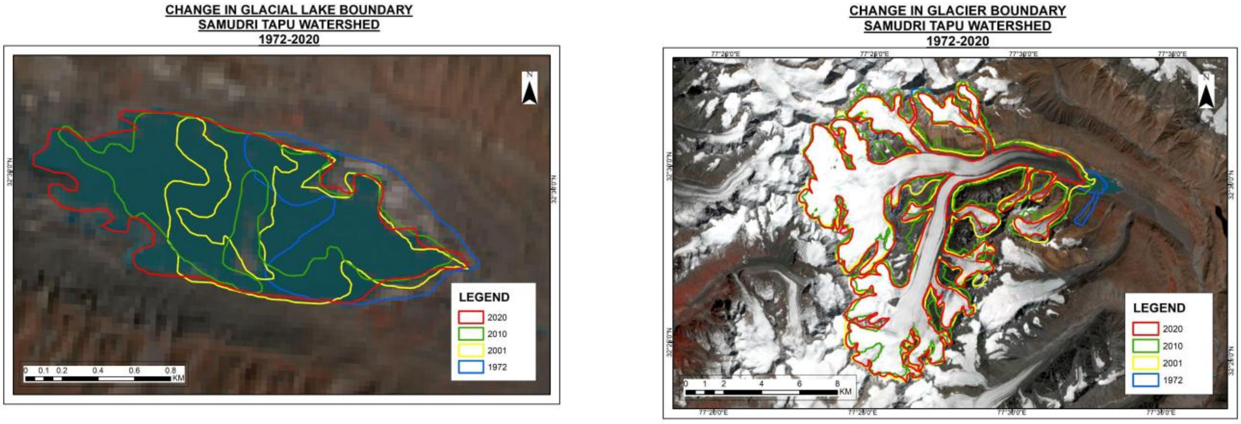



**Fig 4.18 Change in Spatial Extent of Samudra Tapu glacial lake (a) and Samudra Tapu glaciers (b) for 2001, 2010, 2020**

**Plate 28: Field Photographs of Samudra Tapu Lake**

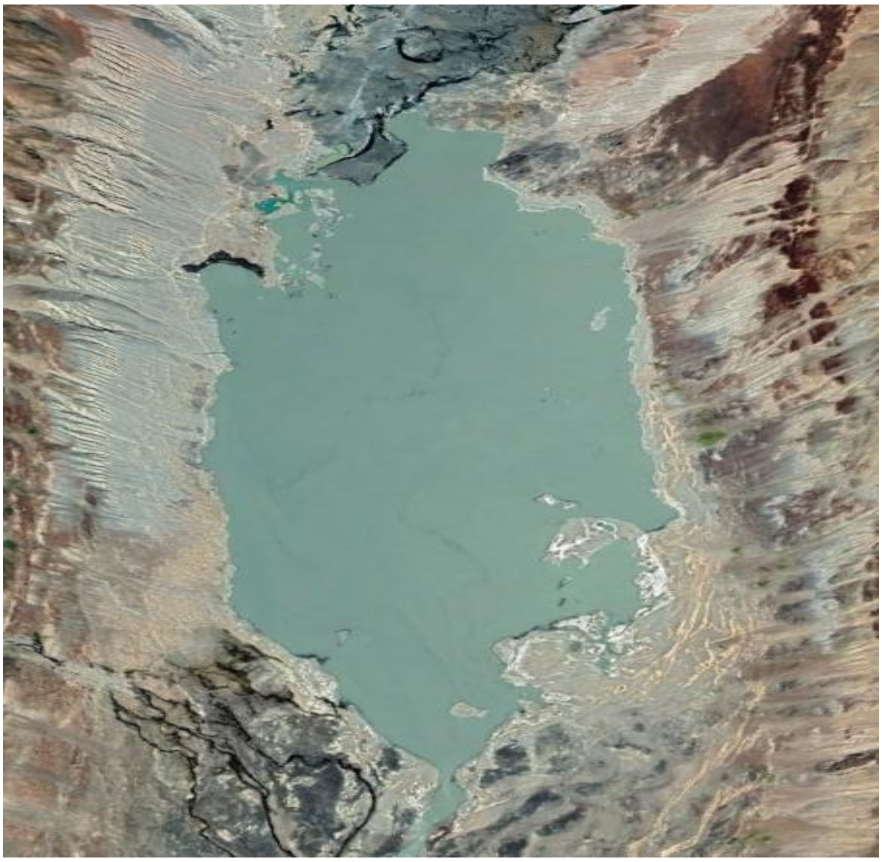


**Fig 4.19 Satellite Image of Samudra Tapu Lake**

## 4.4 ANALYSIS

Sissu and Samudra Tapu pro-glacial lake have shown an increase in its area from 1972 to 2020 and a decrease in glacier area. Calculating the correlation between the decrease in glacier area and the increase in the lake area, we find a strong inverse correlation of -0.9 in case of Sissu Lake but not in case of the Samudra Tapu. It shows that with decreasing size of glaciers there is a gradual increase in the Sissu lake area proportionately. The difference in terms of permanent and seasonal snow cover is also variable. A change of ELA and the snout position of the Sissu glacier has shifted with further glacial melting as studied in previous chapters. Shifting in dimensions of the lake is witnessed along with the changing snout position of the feeder glacier. An increase in the size of the glaciers and the subsequent shifting of the moraine deposits within the glacial environment is also seen during the recent field visits to the glacial lake. In the year 2010, an increase in the snow cover and permanent glacier mass highlights an abnormal heavy precipitation period. From 2001 and 2020, cumulatively there is a decrease in the glaciers and an increase in the glacial lakes. If we look at the boundary of both Sissu glacial lake along with the frontal extension of glacial lakes, there is a lateral and backward extension of the Pro-glacial Sissu glacial lake. In the figure 4.20 and 4.21 for both Samudra tapu and the Sissu lakes, the black line depicts the permanent boundary that has remained constant in every decade while the red dotted line depicts the boundary that has changed temporally. Multiple primary and secondary factors that have led to change in the boundary of these glacial lakes and subsequently causing an outburst floods. Volumetric increase of the lakes enhance the magnitude or degree of disaster because the more the volume the greater is the impact downstream. A primary factor is the overall areal expansion of the lakes in different directions. Both Sissu and Smudra Tapu pro-glacial lakes are bounded by terminal and front-lateral moraine dams. And the linear expansion puts hydrostatic pressure on the dams. This constant pressure of the water can mechanically disturb the balance of the dams. Ripples and surge waves developed in case of higher volume of water can also transfer energy to the materials in dam. This transfer can lead to the melting of ice cores present in the dams by thermal energy transfer. Latent energy released by melting of ice molecules disturbs the thermodynamics of the moraine deposit of dams. This can destabilize and lead to the dismantling of the moraine dam. And both the lakes are bounded by moraine dam that can be dreadful in future. Freeboard of the dam with a definite carrying capacity in case of both the lakes has kept the volume of water in check and restricted its overflow. Water molecules also have their own energy. Volumetric increase of water puts hydrostatic pressure on the moraine sediments. Slow and gradual thrust can also disturb the orientation, arrangement and cohesive strength of the molecular arrangement of the sediment deposits. The presence of ice cores, pebbles, boulders, gravels can cause structural instability of the dams. Constant abrasion of the dam freeboard by the surging water waves, seepage or melting of ice crystals within the dam crest also cause the same. This needs constant monitoring and evaluation since there is a constant increase in volume of both the lakes. In the year 2001, volume of Sissu lake as per Fujita and Huggel was 231.17m3 and 347860 m3 respectively which became 1432.4 and 11432717.18 m3. In the year 2020, the volume increased up to 1588.4 m3 and 31065555.67 m3. This is due to the difference in the empirical constants developed and designed in different geo-physical environmental settings. Same type of increase in lake is evident in Samudra Tapu Lake as well (table 4.5) The increase in volume is a serious concern.

The lateral moraines have got thin and narrow in the west with the lake getting wider. Hence, regular monitoring of the lateral moraines is essential. The right side lateral moraine is relatively narrow, low in height and composed of loose and unconsolidated materials. Therefore it needs further detailed evaluation. There is a presence of large quantities of ice mass in the end moraine. This ice mass if gets melted, will leave coarse materials reducing the cohesive stability of the dams. It is also imperative to evaluate and gauge if there is any probable occurrence of glacier avalanche generating surge waves in the lakes. Blockage of the lake outlets temporarily by the sediment accumulation or blockage by ice debris seasonally can also lead to outburst of lake water. This slow process of discharge from the outlet, seepage flow from the end and lateral moraines, and glacial flow keep the contributions from glacial meltwater in the lakes in check. Sediments and grain size distribution of both the lakes is unevenly distributed in terms of size. The height of the side valleys between lateral moraine and rock slopes were not measured in the field but visually they appeared to have greater elevation than the lakes. Visually collapse of end moraine is more prone than the lateral moraine. Expansion of the lake is more at the frontal sides and towards the ends than lateral expansion. Therefore, limited lateral expansion of the lake has not exerted much pressure on the lateral moraines. But the frontal expansion of the lakes keeps exerting the pressure. In case of extreme events such as heavy rainfall due to cloud burst, rock avalanche, landslide, earthquake or water supply due to sudden melting of glaciers will destabilize the lake in no time. Thus, such secondary parameters need constant assessment and evaluation. There needs to have a close watch at the seepage of the water from the lakes. But apart from hydro-meteorological conditions, the influence of surroundings on the lake atmosphere and vice versa is a prerequisite. This covers the tectonic activities and anthropogenic interference that modify the peripheral lake environment settings. Variation amongst all of these features may influence GLOF hazard levels although prediction is beyond the current competence.

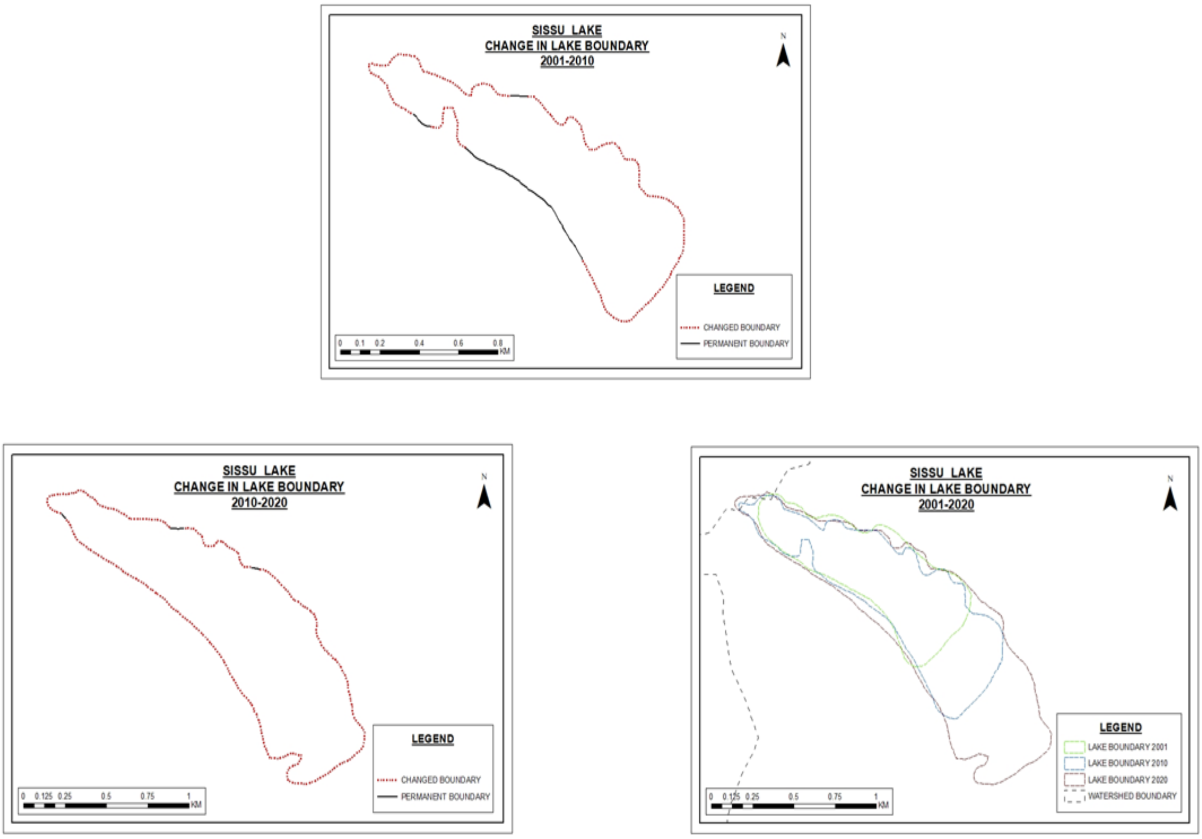



**Fig 4.20 Temporal Changes in Sissu Lake boundary from 2001 to 2020**

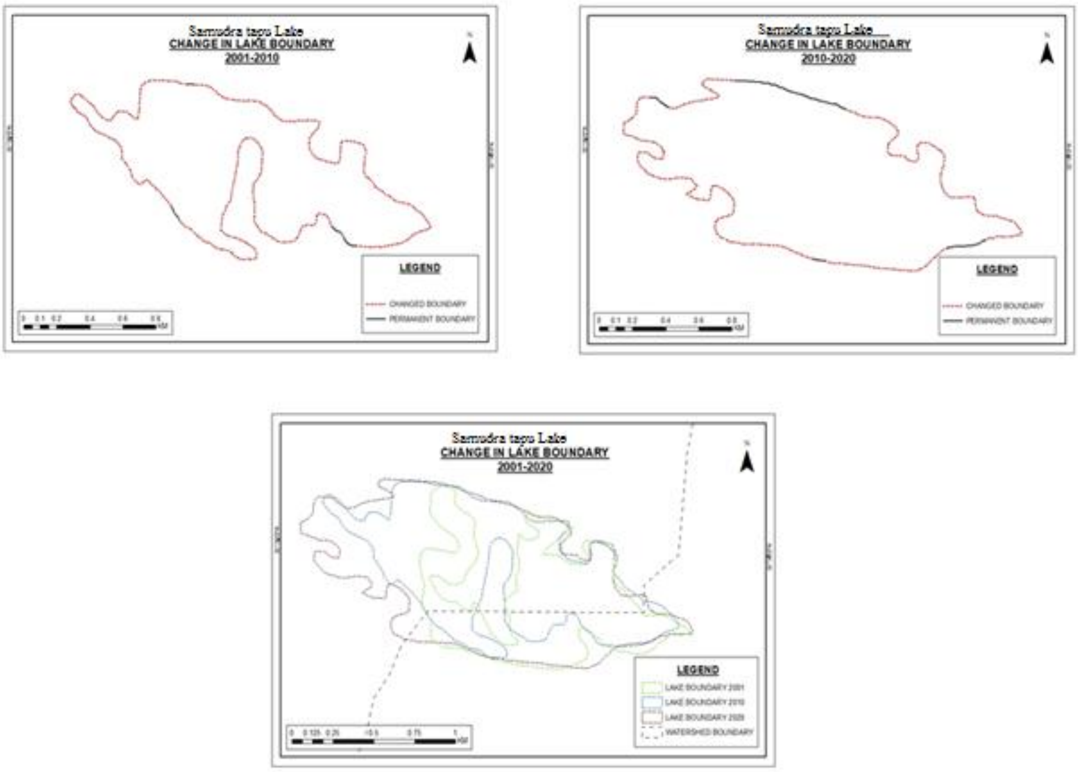



**Fig 4.21 Temporal change in the Samudra Lake boundary from 2001-2020**

| | | | FUJITA | HUGGEL | CHAOHAI |
|---|---|---|---|---|---|
| | YEAR | AREA | VOLUME | VOLUME | VOLUME |
| SISSU | 1972 | 0.199 | 231.1687 | 3478601.724 | 409372807.7 |
| | 2001 | 0.46 | 658.8855 | 11432717.18 | 1218220869 |
| | 2010 | 0.59 | 899.3479 | 16279579.98 | 1684154818 |
| | 2020 | 0.93 | 1588.424 | 31065555.67 | 3044541883 |
| TAPU | 2001 | 0.72 | 1153.528 | 21599588.84 | 2182260058 |
| | 2010 | 0.98 | 1695.881 | 33463731.49 | 3259203109 |
| | 2020 | 1.39 | 2625.011 | 54968559.45 | 5135513678 |

**Table 4.5 Estimated Area Volume through Empirical Formulae**

Sissu and Samudra Tapu watershed, in general, both are barren eroded regions with rocky outcrop surface. Both watersheds have plenty of small and large glaciers which are valley as well as hanging type glaciers. There are quite a few cirque glaciers as well. The entire region has a dense network of small melt water streams coming out from these glaciers. All these meltwater streams join the mainstream. Sissu nala is a glacier fed river. These areas receive scanty rainfall. Though these are dry areas, differential occasions of melting of snow and glaciers have led to the formation of numerous rills and gullies. Sissu watershed is particularly more prone to debris flows and mass movements. There are a few alluvial cones at the toe of the slope. The entire area is an eroded surface with eroded loose and unconsolidated material based on the force and mechanism of gravity. There are large boulder deposits at the bottom of hills where cyclic advance and retreat of glaciers is seen by the alignment of a series of lateral moraines and terminal moraines. It is because of this alternate advance and retreat of glaciers that led to the formation of large pro-glacial lakes at the mouth of the source glaciers dammed by the end moraine complexes.

Mountains of the region are aligned in such a way that they get a sufficient amount of sunlight throughout the year. This has been responsible for the dynamism of this lake and feeder glaciers over the years. And this is a serious issue because this region has a large size of settlement within the valley along with other economically important assets. The most interesting fact of the Sissu Lake is that the meltwater of hanging glaciers have eroded the lateral ridges of the previous glacier extent and drained straight into the lake. This process may have accelerated due to the pressured warming. Samudra Tapu with high potential discharge, Sissu with a high damage potential owing to rapid glacier melting, lake expansion, increased critical peak discharge, high moraine dam and steep valley sides, pose a greater risk of GLOFs. Samudra Tapu and Sissu lakes are critical lakes that need greater human attention as thousands of lives are directly dependent on these lakes for survival and therefore in great danger.

## 4.5 STEPS TO REDUCE LAKE VOLUME

Volumetric increase of lake water will magnify the impact of flooding downstream. It also puts the constant stress on the stability of dams holding lake water. To minimize and reduce the risk, it is imperative to keep the volume of water in check. The melting of glaciers is constantly leading to an increase in the volume, there it is a must to devise and generate new mechanisms and strategies to mechanically reduce and lower the volume of lakes.

### *4.5.1 For water level lowering of glacier lakes the most common techniques are*

***Blowing up of the moraine dam:*** Carefully constructed gaps in the moraine dams to pave a way for a slow and steady movement of water can be one of the possible solutions for lowering the lake volume. But this should be done only after taking enough of precautionary measures and shifting out the population from the downstream area. This proves an early stage mechanism to avoid a sudden outburst.

***Gradual and regular lowering of lake water***: In place of creating gaps or tunnels through moraine dams, there could be a pipe installed in the dam after drilling. These pipes should be installed in selective areas where there is maximum symmetry of dam materials. It should also be well cemented and carefully placed at the strategically best possible location of the dam. However in the Himalayan region,

***The hydraulic syphon technique (HST)***

The aforementioned steps are difficult to execute due to the unpredictable and fragile Himalayan environment. Therefore there is a need for a more practical simplistic mechanism to minimize risk GLOF an even more unpredictable hazard. The most important parameter for such steps to be taken are:

Conserving the structural arrangement and cohesive stability of the moraine dams of the lakes. This reduces the probability of GLOF.

Simple and easy mechanism with operational feasibility.

Low operational and implementation costs.

Hydraulic syphon is a mechanism that works on the principle of hydraulic pressure potential difference between inlets and outlets of pipes with water. Higher pressure difference is an outcome of the reasons mentioned below:

The difference in atmospheric pressure due to temperature difference, altitude gradient and other atmospheric factors such as lapse rate etc.

Density, pressure of water molecules and specific weight of water due to gravity difference depending upon the altitude and latitude of the specific place.

To avoid corrosiveness and internal resistance thrust upon the pipe from the erosion material, the outlet site must be cautiously chosen to select the pipe positioning. Further, the discharge outlet should be placed on a stable surface with concrete protection layers. Alternate freezing and thawing change the density and volume of water. This puts pressure on the surface. Therefore, these tubes must be resistant enough to withstand mechanical pressure exerted by water volume.

An outlet valve also needs to be placed to regulate the discharge amount. Controlled discharge amount can keep the lake water level at the desired level. It will increase the critical limit of the lake storage by adjusting the change in water influx in the periods of enhanced melting. This lowering of lake water should be only up to a secured level to avoid overtopping and burning caused by surge waves. Complete draining out or rapid lowering of water level can worsen the situation even more. Complete and rapid lowering of lake water will expose the dam materials, this exposure will lead to the melting of ice crystals within sediments that eventually can lead to dam failure. This complete drainage of the lake is not justifiable economically as well apart from the technological perspective. This is because the lake serves as a water reservoir for thousands of people downstream. It serves as a constant supply channel to the ‘kuhls’ taking water downstream for daily consumption, irrigation practices and livestock. It also maintains the water budget of the area for a future scenario.

## 4.6 CONCLUSION

Sissu and Samudra Tapu lakes are glacial-fed lakes from their parent glacier along with the associated minor glaciers. Climatic changes and loss of glacier ice mass has added to the volume of both the lakes. The volume of both the lakes have rapidly increased over the years from 1972 to 2020 and this is not going to top in near future. As per the present study, there is a remarkable decrease in the glacier area and a consequent increase in the lake volume. Topography, geology, gradient, aspect and other meteorological parameters increase the vulnerability of the lakes. Volumetric size and expansion, type and orientation of the lakes with respect to the feeder glaciers, structure and arrangement of the dams has made these two lakes even more vulnerable. The presence of large settlements and critical infrastructure makes these lakes more prone to cause large scale damage. Therefore, there is a need to regulate and robust monitoring and management of the lakes to avoid any unforeseen calamities saving lives, economy and the environment.

# CHAPTER 5

# FLOOD INUNDATION MAPPING

## 5.1 INTRODUCTION

Glacial lake outburst hazard is witnessing an increasing trend globally. The spatio-temporal increase of Sissu and Samudra tapu glacial lakes in terms of area and volume increases the imminent danger of potential GLOF. Once PDGLs are identified, it necessitates the identification of the geographical extent of the resulting GLOF event to quantify the damage potential. In this particular study, the HEC-RAS 1D model was used to simulate the probable and hypothetical GLOF from the Sissu Lake. Sissu and Sashin are two large villages in the downstream valley with a relatively large populations. The population living in the valley area down the Sissu lake is increasing. Large population here is dependent on Sissu nalah water draining out from the Sissu lake for different kinds of economic and social purposes. There is a bridge connecting Lahaul to Ladakh and rest of India via Manali. There are other crucial infrastructures such as a helipad, hospitals, schools, hydel power plants etc. near the villages which is likely under threat in case of probable outburst. There is a vast pasture stretch in the region, used as grazing fields by yaks and sheep of the local trans-human in summers. Agriculture a predominant economic activity is also practiced downstream on large scale. Hence livestock and pastures are at a greater risk of damage in case of the GLOF. Relatively large population with respect to other villages in the district, abundance of critical, physical and cultural infrastructures, its relative geographical importance for connecting Lahaul and Ladakh with the rest of the country viva Manali makes it an important to study if at all the region will get inundated in case of the outburst of glacial lakes.

It is further important to analyze GLOF associated risks to save and minimize the inherent loss by preparing suitable mitigation strategies and early measures. Economic activities are penetrating at the higher altitudes in the Himalayan region. In the wake of this, several small and big hydel power projects have also moved into the higher Himalayan region for the availability of perennial water supply (Shrestha et al., 2010). For this particular purpose, a potential threat of GLOF on the Sissu region is assessed only. Due to paucity of time and lack of crucial ground leveled detailed data sets, 2D modeling and the dam break modelling could not be done. 1D modelling using Hec-Ras 6.0 version, flood inundation map is prepared to know the area and features likely to get flooded. This also forms an important thematic layer for further vulnerability assessment. This study has used Hec-Ras 6.0 to calculate flow depths and inundation mapping. The field investigation of the lakes also found that end moraine and lateral moraine lakes consist of loose and unconsolidated moraines, making them unstable. Moraine dams of the lakes are steep. Distance of the lake from the parent glacier is negligible, i.e. but 1 meter. (Parent glaciers along with tributary glaciers are supplying melt water to the lake as well. Above mentioned geographical, social, economic and the environmental factors make the lake vulnerable and to look into the area possibly getting affected.

## 5.2 DATABASE

- ALOSPALSAR DEM downloaded from https://search.asf.alaska.edu/ for the date 10th August, 2007.
- Bathymetric data for better calculation of depth of lake
- The manning's roughness coefficient values pertaining to every LULC classes were taken fromsecondarysources-https://www.engineeringtoolbox.com/ mannings-roughness-d_799.html and the HEC-RAS Hydraulic Reference Manual Version 5.0, February 2016, which was available in the downloaded HEC-RAS 5.0 application.

## 5.3 METHODOLOGY

- Processing the DEM
    - The dam was checked to see if there is requirement of any void filling.
    - The acquired DEM had no voids so the usual watershed delineation procedures were carried out. The DEM was filled for any sinks following which, flow direction and flow accumulation functions were run from the hydrology tools in ARCGIS 10.5.
    - Using raster calculation a threshold value of 275000 was fixed to derive the stream raster. This helped delineate the Sissu Nala. This was confirmed by underlying a base map from google maps and Landsat FCC.

- Creating the flood inundation map
    - The geometry was created using HECgeoRAS in ArcGIS 10.5. The geometry consisted of a river traced from the previously derived the Sissu nala shapefile. It also consisted of bank lines, drawn to trace the banks of the river or stream, flow paths, drawn to trace the direction and line of flow along the bank and XS cut lines. These cut lines were drawn from downstream left bank to right bank as per conventions and perpendicular to the stream. These demarcate the cross-sections along the stream. XS cut lines were drawn automatically 1500 meters long with an interval of 250 meters. This made sure the cut lines were efficiently drawn. However, the cut lines were manually edited to better suit the concerned area. Eventually, 49 XS cut lines were drawn of various lengths to suit the study area. The position of these XS cut lines also marked the points where the application would construct a cross-section.
    - This geometry file was then opened in HEC-RAS 5.0.7 for further analysis.
    - The dominant land use and the land cover class were considered for each cross section while assigning the manning's roughness coefficient. The manning's roughness coefficient for every XS cut lines were taken into consideration and for the few cut lines which intersected different LULC, the coefficient value was averaged. Eventually, these values acted as inputs for the conditions of each cross- section in HEC-RAS 5.0.7.

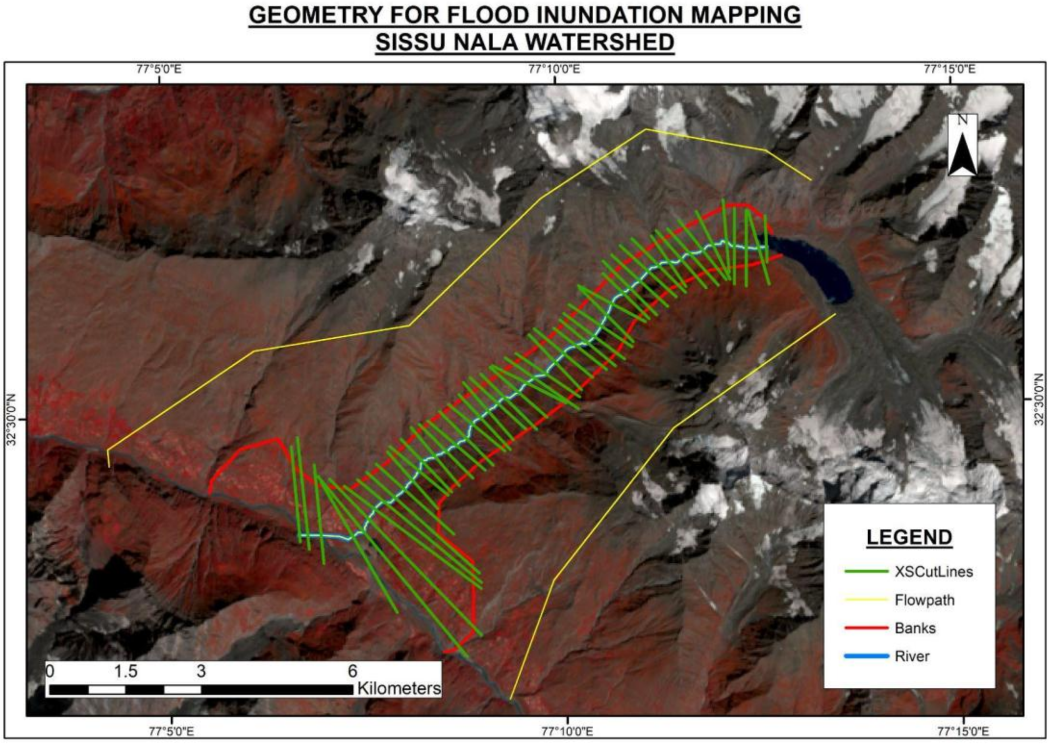



**Fig 5.1 Manual and Digital generated XS lines for Sissu nalah.**

| S.No. of XS Cut Lines | Manning's Roughness Coefficient | Peak Flow at the location (in cubic meters per second) |
|---|---|---|
| 1 (at the mouth of the Sissu nalah) | 0.15 | 2978.421 |
| 2 | 0.15 | 2989.068 |
| 3 | 0.012 | 2989.789 |
| 4 | 0.012 | 2992.557 |
| 5 | 0.087 | 2983.082 |
| 6 | 0.15 | 3040.287 |
| 7 | 0.15 | 3071.781 |
| 8 | 0.087 | 3086.154 |
| 9 | 0.15 | 3127.024 |
| 10 | 0.15 | 3148.24 |
| 11 | 0.15 | 3174.548 |
| 12 | 0.15 | 3192.314 |
| 13 | 0.15 | 3216.621 |

| | | |
|---|---|---|
| 14 | 0.15 | 3242.499 |
| 15 | 0.15 | 3278.093 |
| 16 | 0.15 | 3299.566 |
| 17 | 0.15 | 3315.481 |
| 18 | 0.15 | 3340.733 |
| 19 | 0.15 | 3355.698 |
| 20 | 0.15 | 3361.292 |
| 21 | 0.035 | 3363.287 |
| 22 | 0.035 | 3383.523 |
| 23 | 0.035 | 3401.083 |
| 24 | 0.035 | 3431.888 |
| 25 | 0.0925 | 3465.162 |
| 26 | 0.0925 | 3471.466 |
| 27 | 0.03 | 3508.451 |
| 28 | 0.03 | 3509.621 |
| 29 | 0.03 | 3539.131 |
| 30 | 0.03 | 3563.31 |
| 31 | 0.03 | 3588.576 |
| 32 | 0.03 | 3639.791 |
| 33 | 0.03 | 3718.449 |
| 34 | 0.03 | 3748.729 |
| 35 | 0.03 | 3785.574 |
| 36 | 0.03 | 3806.066 |
| 37 | 0.03 | 3840.713 |
| 38 | 0.03 | 3873.733 |
| 39 | 0.03 | 3914.61 |
| 40 | 0.03 | 3927.32 |
| 41 | 0.03 | 3941.808 |
| 42 | 0.03 | 3956.722 |
| 43 | 0.03 | 3955.937 |
| 44 | 0.03 | 3969.588 |

| | | |
|---|---|---|
| 45 | 0.03 | 3979.895 |
| 46 | 0.03 | 3984.817 |
| 47 | 0.03 | 4019.527 |
| 48 | 0.03 | 4039.497 |
| 49(at the source of Sissu nalah) | 0.03 | 4044.662 |

**Table 5.1: Showing the Manning's Roughness Coefficient for Each XS Cut lines**

- Equations to determine the depth, volume and peak flow from the area of the lake were used. From our pre-calculated area of the lake, the volume of water was calculated using Arendt's formula. Post which, Huggel's formula was used to calculate the peak flow or Qmax. These values served as the input values for determining the steady flow in HEC RAS.
- Using the 3D Analyst tool from ARCGIS 10.5, the longitudinal profile of the Sissu nalah was plotted. This enabled us to calculate the average slope of the stream. The average slope thus calculated was 0.092, which was another input for determining the flow conditions.
- Following this, a steady state flow was calculated using the HEC RAS software and the results were opened in the ARCGIS 10.5 for better visual understanding.
- Eventually, a flood inundation map was determined.

| Area in $km^2$ | Volume in $m^3$ ( using Huggel et al) | Qmax in $m^3/s$ (Using Arendt et al) |
|---|---|---|
| 0.93 | 31065556 | 46819.61 |

**Table 5.2: Area of Sissu Lake and Calculated Volume and Peak Discharge**

## 5.4 HYDRAULIC MODELLING

Glacier lake outburst floods are extremely unsteady flows pronounced with high fluctuations in their flow path down the valley. It can appear as a normal flood to hyper flow with great velocity. It can also look like a river flooded with huge boulders and debris flow (Kershaw et al., 2005; Mergili et al., 2011; Manville et al., 2012; Worni et al., 2012a). Several hydro-dynamic models have been developed to simulate steady and unsteady flood mapping. But due to data constraints here HEC-RAS 1D modelling is used for the propagation of GLOFs simulation. Further, Alho and Aaltonen (2008) have demonstrated that the 1D flood model computed through HEC-RAS is a simple and easy graph that can easily be compared with results from other models too. But, it has limited applicability in terms of value as the tabulated results are uncertain. The results is also sometimes oversimplified with no precise calibration of the extent of the flood inundation. (Byers et al., 2013).

Manning's n value utilized in the Hec-Ras 1d modelling may be a coefficient value that signifies frictional relationship between two surfaces. This co-efficient value depends on roughness coefficient, shape, size and flow constriction of a channel, stage and amount of discharge, irregularities within the flow, sediment load and conditions of the bed rock. The specific values for every cross-section were put in mentioned in table above. The Manning's roughness coefficient for the Sissu region ranges from 0.03 to 0.15 (Chow, 1959, HEC-RAS Manual HEC, 2010). Sissu stream with mountainous terrain in upper reaches having gravel, cobbles and boulders. Thus, the model has been run with different sets of Manning's coefficient values. Due to the paucity of time Manning's co-efficient value couldn't be calculated at every single position. Therefore, the data sets from the manual is employed during this study. There is an opportunity for overestimation and underestimation at some points. There is an opportunity of error within the modelling also. It had been found that a ten to extend in Manning's n values triggered a decrease within the peak discharge by up to 9 %. This study has focused only on developing the scenario that's flood inundation map for Sissu glacial lake.

## 5.5 RESULTS AND DISCUSSION

### *5.5.1 Flood Inundation for SISSU Glacial Lake*

The Sissu glacial lake is in close vicinity of the Sissu and Shashin villages. These are densely populated villages with a large number of physical, cultural and social infrastructure. The Sissu nalah originated from the Sissu lake is an important source for the lives of the people of both the villages in terms of irrigation, recreational purposes, hydroelectricity and other such purposes. Flood inundation map prepared through the Hec-Ras 1D modelling presents a worrisome picture in terms of the loss and disaster.

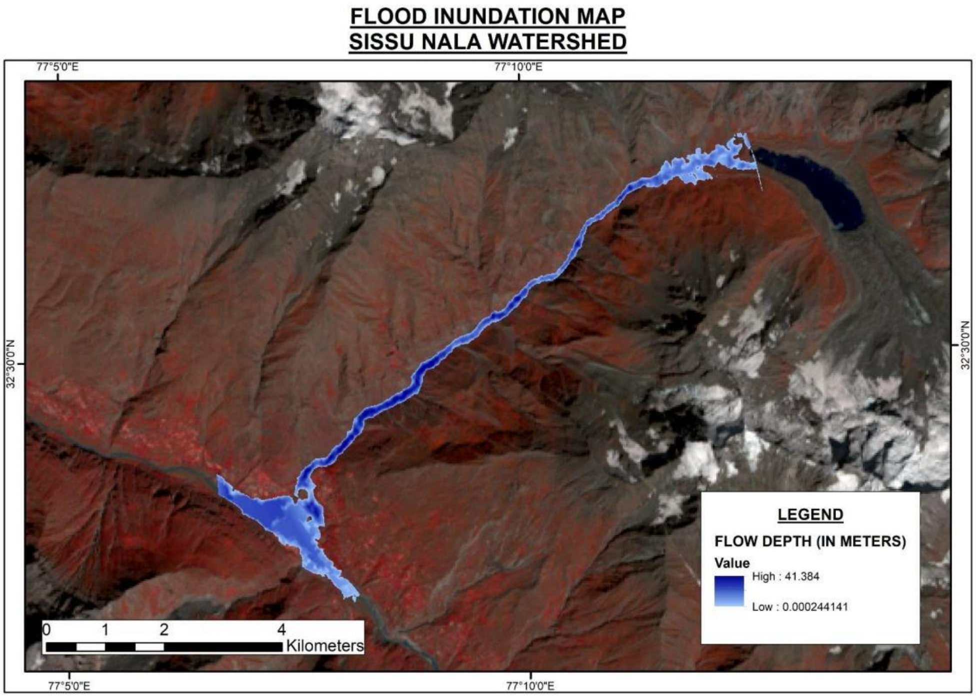



**Fig 5.2 Flow Depth of Sissu Nalah through Sissu Glacial Lake**

The results of the HEC-RAS 1D model shows that the maximum peak discharge is 46820 cubic meter per second and the total water volume estimated is 31065556 cubic meter per second while the total inundated area is 3.04 $km^2$. Results of the flood inundation mapping depict that the flow depth varies from 0.0002 meters to 41.38 meters (Fig. 5.2). As per the simulated map, the flow depth of more than 20 meters could exist for 3.5 km for the Sissu nalah before it intersects the Leh-Ladakh Highway. The flow depth increases beyond 25 meters around 4.5 km upstream from the Leh-Ladakh highway for about 1km; and then again briefly for a few hundred meters around 6km upstream and 7 km upstream. Overall, the mean flow depth is 13.221 meters, equivalent to a 5 storey-building. This flow depth depicts the intensity of the GLOF event with higher flow depth signifying areas with maximum probable loss carrying larger volume of water. This flow is visible in the figure 5.2 with darker shades of blue color depicting higher flow depth. This variable flow is also an outcome of topography and slope of the region.

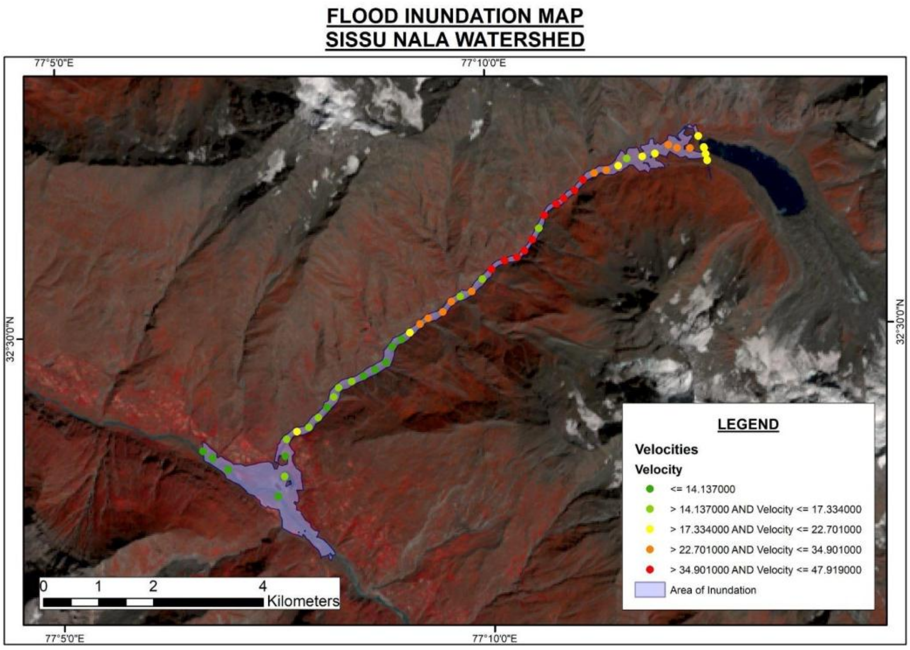



**Fig 5.3 1-D Flood Velocity Map for Sissu Watershed**

The figure 5.3, shows the distribution of the flood velocities at different altitudes. Red dot shows highest velocity of flood water while green dot shows the least velocity. Yellow dots are the regions with intermediate velocity. The velocity at the mountainous terrain is a slope and an elevation dependent indicator. Therefore, higher the elevation and slope, higher is the velocity. In this case, the flow velocity ranges from 1.87 m/s to 47 m/s. The flow velocity is the highest in the upstream region where the valley is narrowest and the slope is steep. Such a flow extends for approximately 2.5 km. The flow velocity is least near the helipad- 1.87 m/s.

As per the simulated map, the water inundates almost 20 percent of Sissu village but the major part of the Shashin village remains out of the inundated area. Cultural infrastructure of the Shashin village like the Gepang Nath temple associated with identity of the village remains unaffected. 20 percent of settlements of the Sissu are likely to get inundated. Helipad, hydel power projects, national highway connecting Manali to Leh and connecting bridge on the Sissu are some of the critical infrastructures likely to get devastated by the outburst as shown by the flood inundation results (Fig 5.4).Loss of the bridge by the outburst floods will not only disrupt the transportation and communication facilities but also hinder the long term essential supplies and evacuation process along with revival of economic activities. Another major direct loss is agricultural fields. Agricultural practices on the terraces by people of the Sissu village are directly under the threat of getting inundated by the peak flow (Fig 5.4). Though a large part of the Sissu and Shashin villages are strategically located in such a way that they are out of direct loss in terms of loss of lives, they still may be impacted. Following any event of Lake Outburst and subsequent inundation or events of heavy precipitation leading to such an outburst, the soil is highly saturated. Incidences of soil piping, land subsidence and landslides may occur. This in turn would pose a threat to the structural integrity of the nearby concrete structures. This will also threaten the areas under forest, grazing lands for livestock and agricultural areas in the adjoining areas. People of Sissu and Shashin are dependent on Sissu nalah from the Sissu glacial lake for supply of water in many ways downstream. The lake outburst will have a dire consequences from an economic perspective. Ecologically, it will bring imperceptible changes to the region. Supply of large boulders, pebbles and other moraine sediments downstream will damage the local micro topographical conditions in the long term. The presence of material downstream will alter the surface and sub-surface flow of water. Eventually, the processes of weathering and the mass movements would alter the geomorphological landscape of the region, snowballing a positive feedback system.

Likewise, parts of the Sissu village and market may be affected. Such a high velocity flow, coupled with debris, post an outburst, also has the potential to cause physical damage to life and property downstream, even if it lies beyond the direct area of inundation. The flow of the Sissu nalah may be interrupted or clogged and the stream may divert or change its course to the next best route. This changed route of the river will further lead to changes in the geo-environmental settings and human interactions within the local region. This whole process not just leads to destruction of area directly inundated but can also change and alter the land use land cover of the surrounding region. This can show its negative consequences in future if not anytime soon. In this scenario, the configuration of our inundation mapping would change. Helipad, bridge, agricultural lands, Leh-Manali Highway, terrace cultivation, Hydro-electric power project and Sissu Govt School and PWD rest house is directly within the inundated area. Sissu bridge and other features with an altitude of 3400 meters above MSL at the 6th and 8th XS Cutline, respectively, has a flow depth of 21 meters and 14 meters, respectively, with a peak flow of around 3040 cubic meters per second and 3086 cubic meters per second, respectively. There is every possibility that the structure of the bridge would be affected and may even get washed away following the outburst. ALOS PALSAR dataset is a Digital Terrain Model or DTM, i.e. it plots the natural terrain of the region, overlooking the surface features including buildings and bridges. Therefore, a flow depth of 21 meters plotted with the help of a DTM clearly signifies that any surface man-made features of such a height and below that height, is bound to get flooded. Thus, the Sissu Bridge will be critically damaged. Using the same empirical formulae, volume and peak discharge of Sissu glacial lake has been calculated for 2040 time period. If we look at the scenario of 2040, the situation gets even more worsen. The Sissu lake further gets bigger in size compensated with decrease of the source glaciers within Sissu watershed. Therefore, inundation area encompasses more area. With the current rate of development projects, loss and damage is likely to be even more as evident by the hypothetical flood model created for 2040 (Fig 5.8)

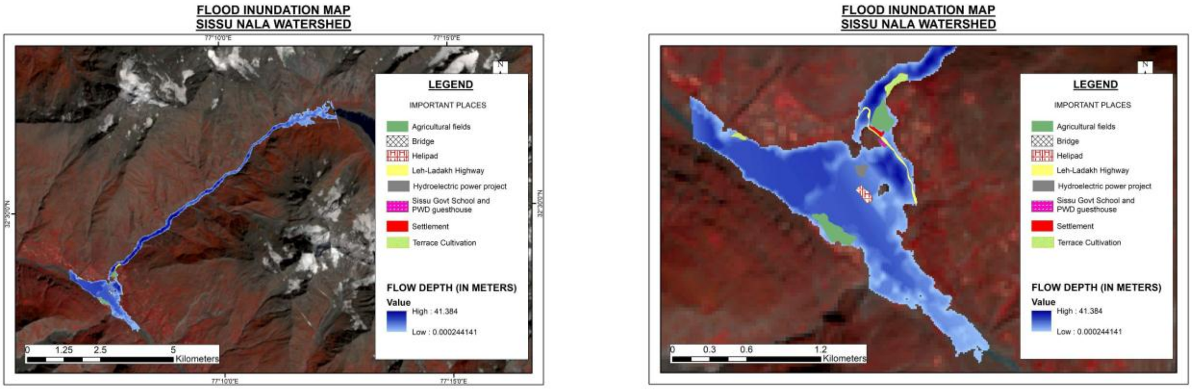



**Fig 5.4 Infrastructure under threat Covered Within the Flood Inundation map.**

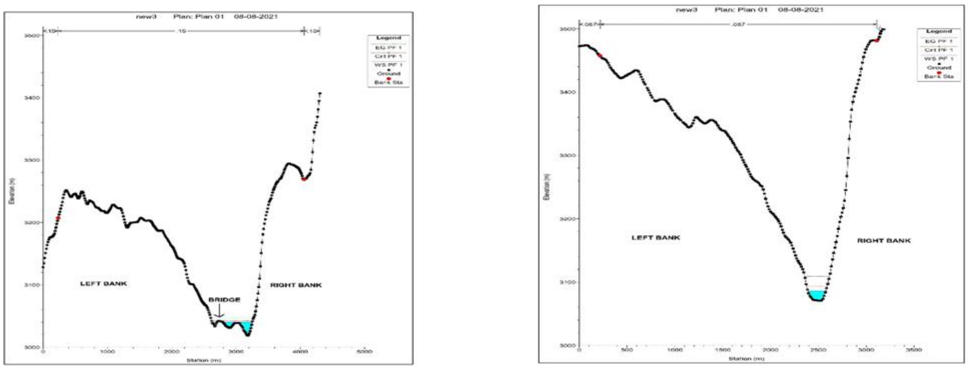



**Fig 5.5 Empirical Estimated Peak Discharge Volume of Sissu lake**

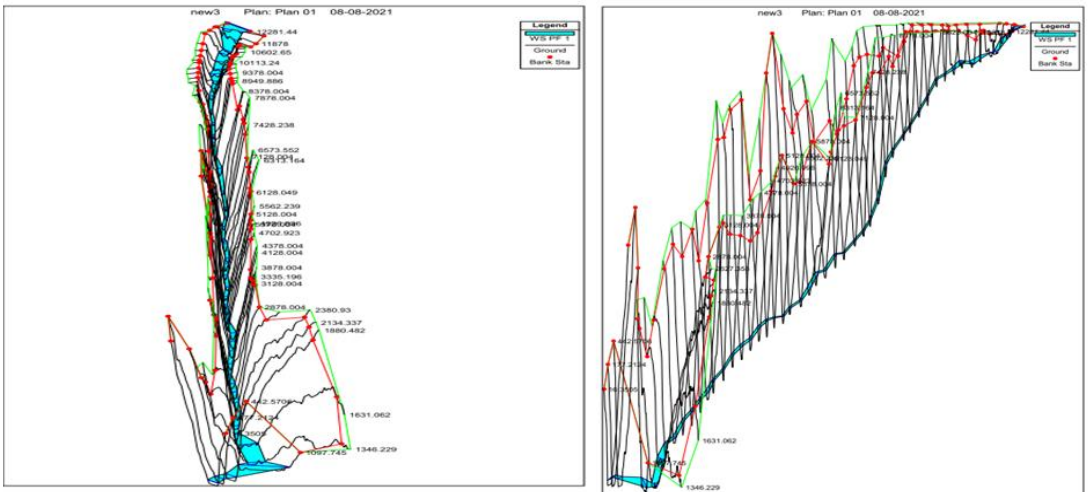



**Fig 5.6 Left bank and Right bank flow path of Sissu stream in case of peak flow (result obtained through Hec-Ras)**

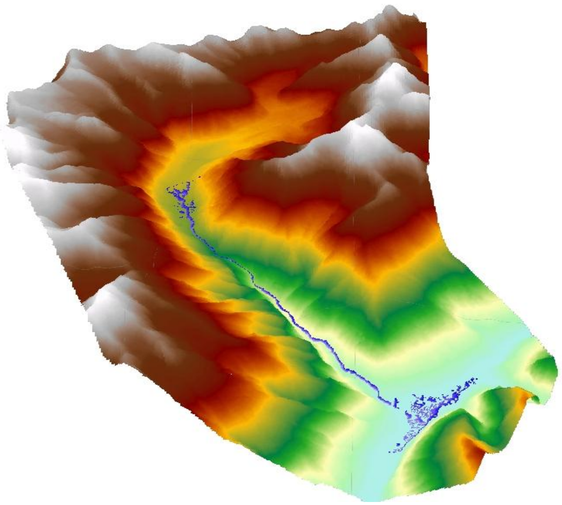


**Fig 5.7 3DView of Sissu Nalah Flow within the Catchment Obtained Through Hec-Ras.**

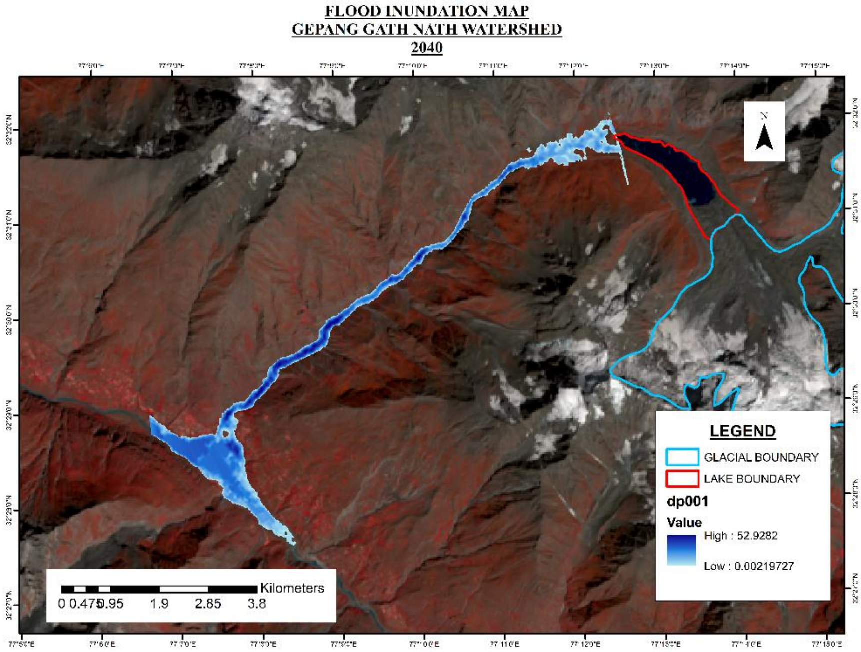



**Fig 5.8 Flood Inundation map of Sissu Glacial Lake, 2040**

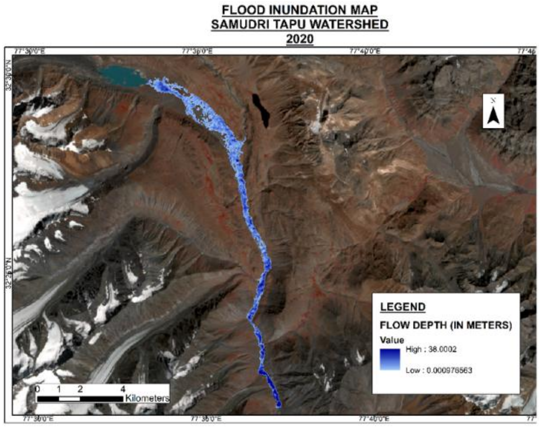

**Plate 29: Field photographs of Leh-Manali Highway and Sissu Bridge impacted under Flood Inundated area.**

**Plate 30: PWD guest house in Sissu area under the Impact of Flood Inundation**

**Plate 31: Field Photograph of Helipad in Sissu included within the Food Inundation Area.**

### *5.5.2 Flood Inundation for Samudra  Tapu Glacial Lake*

The Samudra tapu is also a pro-glacial lake. But it’s a shallow glacial lake within a wide and flat valley region. Since Samudra tapu is a shallow glacial lake, it holds less amount of water. The valley is also too wide. Hence, the flow depth and flow velocity are not that high and depicts much less variation along the wide valley within the lake stream flowing out of the Samudra tapu in case of the outburst events (Fig 5.9). ELA calculation and glacier area change detection in the previous chapter depicts no such amount of loss in the glacier area within the Samudra tapu watershed in previous decade. Since there is no loss in the glacier area, it is least likely to add much glacial melt water in Samudra tapu glacial lake. Available small amount of the lake water generates very small peak discharge values in case of any outburst flood scenario according to the flood indundation mapping results obtained from Hec-Ras 1 D modelling. The parameters used here such as Manning coefficient, peak discharge and volume is listed in appendix. Even in the case of cloudburst or rapid glacial melting, the lake is large enough in terms of area to hold enough water. The region is also barren with no such social and economic infrastructure, except for non-metallic roadways build by BRO which is likely to get damaged in case of outburst. Tandi bridge at the confluence of Chandra and Bhaga stream is at a much greater discharge. There, the bridge is also very unlikely to be under threat (Fig 5.10)



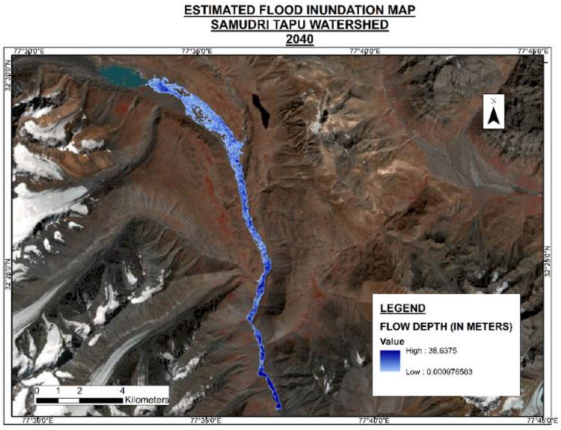




**Fig. 5.9 Flood inundation Area of Samudra Tapu watershed with peak velocity**

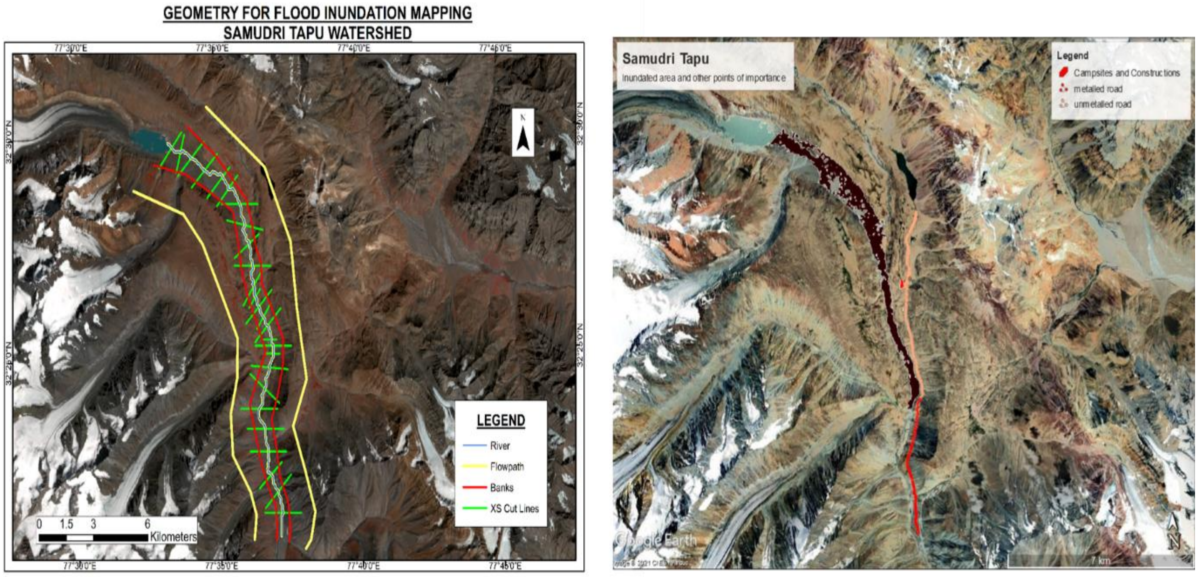



**Fig 5.10 Flood Inundation Area Likely To Get Damaged**

## 5.6 LIMITATIONS OF THE STUDY

- Misfit of available dataset:
    - The width of the Sissu nalah ranged between 6.79 meters to 21.3 meters. The spatial resolution of the DEM used is 12.5 meters. Such a difference in resolution of the dataset makes the study of a small feature erroneous. The High Mountain Asia DEM or HMA DEM with a resolution of 8 meters was a good alternative to ALOS PALSAR that was used. However, the amount of void in the HMA DEM rendered it improper to be used even after void-filling image functions. Filling wide voids with algorithms would generalize the elevation to such an extent that our objective of studying the stream in a mountainous terrain would be compromised. Therefore, using a dataset of 12.5 meters was not the best option, but the better option as opposed to HMA.
    - The DEM that was used belonged to the year 2009, while the lake area calculated belonged to the year 2020. Over the years, changes in elevation and slope due to diastrophism and exogenic processes are very much

possible. This can slightly alter the results. Due to the limited availability of DEM, this flaw was overlooked.

- Current meter is an instrument if used could provide the real-time discharge data of Sissu stream at various points to be further used for detailed HEC RAS 2D modelling. This could have helped in preparing the flood hydrographs. But due to difficult terrain and unfavorable weather conditions for 2 consecutive years, precise and accurate discharge data could not be calculated. Besides, there is no local gauge stations to measure discharge data near the Sissu stream or even in the nearby areas. Therefore, empirical formulas were used for further study.

- With the available bathymetric data of the lake depth, the estimated volume came to be an unprecedented amount. This questioned the reliability and the processing of the data. Therefore, to aid our flood simulation, predetermined formulas for calculating depth, volume and peak flow were used. These formulas are generalized and each gives an output very different from the other. This poses a question as to which of these outcomes aptly represents the real scenario. Based on field experience, the most believable values of depth, volume and peak flow were chosen.

- Improper estimation:
  - Assuming ceteris paribus, for several variables, the peak flow can suffer from over and underestimation. Though the effort was made to make sure the least error possible, the results can be refined further with the availability of finer resolution DEM and optical datasets, field discharge data and detailed LULC, all for the same time period.

## 5.7 CONCLUSION

Increasing incidences of GLOF in Nepal and Tibet have captured the attention on the processes and aftermaths of the disaster. Looking at its cross-boundary severe devastation stretching to areas across continents within a short span of time makes it even worse. This makes it difficult to provide any early warning mechanism to prepare against the disaster. Gradually the attention on glacial lakes and associated GLOF hazard has diverted to Himalayan glaciers and glacial lakes. Till now the effort has been on creating an inventory of glacial lakes but mere inventory and dynamics of lakes will not serve the purpose of avoiding the threat. Therefore, flood inundation mapping through various available models helps in building a probable scenario of the areas to be impacted directly by the outburst floods. 1D HEC-RAS has yielded flood inundation maps that give us an insight into the degree and intensity of destruction. This also gave us details of the total area under the impact, critical infrastructures and the cultural, social, economic and the environmental loss. Prepared flood inundated map helps to classify the intensity of flood, based on the calculated range of depths at different levels. This provides information on probable hazard and depicts that only a small section of village houses would be exposed to the flood of a medium-intensity. The calculated flood characteristics might not accurately represent values, possibly underestimate peak discharge and flow depths while overestimating the flow velocities. Despite all the limitations and problems mentioned in the calculated model, there is variable good accuracy between the tabulated results and the information of the perceived threat obtained during fieldwork, accounts of the local villagers, and the work of independent research teams. This result can further act as a sub-set to predict the degree of loss, precise discharge amounts at various levels, time interval taken to reach downstream in more detail and accurately with the field investigations. There should be measures taken to ensure the early warning mechanism, timely evacuation and rehabilitation strategies for the affected ones. Increasing encroachment on the areas close to glaciers for hydroelectricity generation, popular tourism sectors near the glaciated regions, and other commercial activities need to plan after the assessment the damage potential. New construction of infrastructural activities should be done only outside the area of inundation. Therefore flood simulation should be the key parameter to consider before planning new projects, plans, policies by the policymakers and governmental authorities.

## 5.8 PROPOSED ALTERNATE ROUTE

The relevance and importance of the Sissu bridge has already been highlighted in the present studies. This bridge is likely to get damaged in case of the GLOF as depicted in the flood inundation map. In order to avoid the overdependence on the Sissu Bridge for multiple purposes, there could an alternative route constructed near the preexisting bridge above the flow depth obtained through the HEC-RAS data. This bridge connecting the Sissu and Shashin village should be constructed at a minimum depth of 50 meters (Fig. 5.11). This would not only reduce the overburden on the present Sissu bridge also if it gets damaged, rescue and rehabilitation works will also be easy. It would keep the connectivity intact. It is also important from the defense and strategic purposes. It would also not stop the movement of defense forces and supplies of their essentials to the forces deployed in Ladakh. It will fasten the process of rescue, thus reducing the number of causalities in the case of GLOF or any other such disaster.

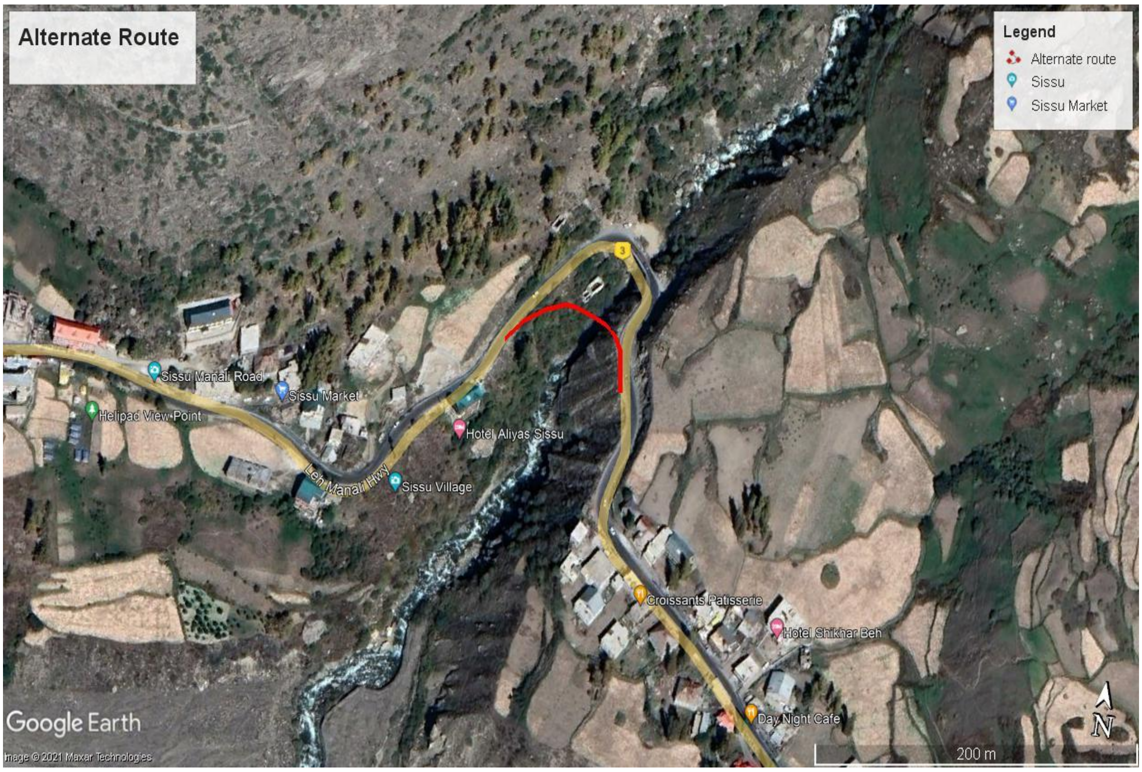



**Fig 5.11 Suggested Alternate Route around the Sissu Bridge**

# CHAPTER 6

# HAZARD AND VULNERABILITY ASSESSMENT

## 6.1 INTRODUCTION

The Himalayan glaciers are melting and decreasing at a very high rate with the likelihood of its disappearance by 2035 if the present rate remains unchecked. Climatic changes not only impact the physical and geographical environment, but it also has socio- cultural, political and economic impacts. Climatic changes not only disturb the physical geomorphic settings changing the landscape, but it also impacts the supply of freshwater water for drinking, irrigation and hydel power projects. Quantitative spatial and temporal loss of ice and snow will also lead to loss of biodiversity modifying the high altitude ecosystem. More than a billion people's lives are dependent on the Himalayan glaciers for the sustenance in the South-East Asia in so many ways. Basically the Himalayan glaciers are the backbone for economic development. Several studies depict that climate change can enhance the frequency and magnitude of natural hazards (Haeberli, 1998). Glacial Hazards are the geo-physical processes that has the potential to cause loss of lives, destruction of social physical and economic structures within human societies (Reynolds, 1992). Glacial lake outburst floods may not or never pose any threat to mankind, but atmospheric warming, increasing human reach to the vicinity of glaciers, development of infrastructural settings in the alpine environment has increased the potential threat of glacial lake outburst floods (GLOF). Incidences of increase in GLOF across the globe are a serious concern. Historical records of 33 Himalayan GLOFs depict increase in the frequency of the event. The increase in size of present lakes are increasing in most of the regions while moraine-dams are getting weaker (Reynolds, 1998; Yamada 1993).Post Nepal (Dig Tsho - 1985) , Bhutan (Luggye Tsho – 1994) , Kedarnath floods caused by the Chorabari lake and the recent being Chamoli disaster has increased public attention and governmental focus of late. GLOF hazard assessments is a prequisite for disaster preparedness in order to ensure early warning mitigation measures to avoid irreplaceable damage.

## 6.2 THE HIMALAYAN SOCIETY

The societies of the Himalayas are carved out of dependency on the natural climate for livelihood and sustenance. Erstwhile de-glaciated valleys have been populated by village communities. Their development has taken place with the help of knowledge passed on through generations in coherence with micro-regional settings. Harsher climates in higher altitudes have forced communities to resettle in areas of lower elevations during the late Holocene period following the manifestations of the local Little Ice Age. Relicts of settlements in far-off remote regions prove the fact that climatic variability shaped the choice of habitation amongst the mountain communities. Presently the economic needs of the societies have influenced the choices of crops depending upon the growth potential of the land, and viable growing period. This has resulted in higher production of commercially popular crops that fetch the local cultivators, the means for a semi subsistent and market-oriented production pattern. Very few surveys have been conducted at the micro-level oriented towards the perception of the locals regarding changing climate and its ramifications on the immediate environment and subsequently on their livelihoods. Therefore, the perception study method has been utilized for understanding the link between the perception of climate and its socio-economic impact. Small regions, especially in the non-homogenous mountainous regions, are very critically influenced by weather and physiographic parameters that need to be identified within the deep ecosystem. This helps in understanding the cumulative change in society as a result of a change in the environmental factors. Indigenous people's perception would help miles in understanding the behavior of nature due to their close ties to their livelihoods. Such local knowledge needs to be acknowledged to formulate mitigation strategies in case of any distress. The mitigation strategies would include better coordination between science, technology, management, communities, and policy-making.

## 6.3 HAZARD AND DISASTER

As per United Nations International Strategy for Disaster Reduction (UNISDR), a hazard is a phenomenon that causes negative impacts on the economy, society and environment encompassing both natural and anthropogenic factors related to the event. Hazard is that the precursor of disasters causing widespread damage. In other words, a hazard is a process or an activity that causes loss of lives, injury and health damage, infrastructure damage and other social economic and environmental damage. A Hazard could be a single event or chain each with its own characteristics and process. There are 6 major categories of natural hazards that could be classified as Geological, hydrological, climatological, Biological and extra-terrestrial hazards. This hazard system comprise of natural, human, and environmental aspects mostly an outcome of natural environmental factors. Natural hazards have variable regional distribution intrinsically linked with the local environmental settings. Regions with high tectonic movement and environmentally fragile have a high degree of hazards with higher frequency, intensity and magnitude and vice versa. Risk in an area is a function of hazard and damage potential where damage is loss of social capital, critical infrastructure, vital assets and loss of lives. This factor is directly dependent on the vulnerability of the population while the vulnerability is further a by-product of socio, political, economic and geographic aspects. Hazards of any intensity and magnitude are dangerous for mankind. While a disaster is a state that poses serious and widespread damage of human life, health, property or the environment either from natural or anthropogenic causes(IFRC,2007).Here three things are important to note in case of disaster viz: the destructions of society, loss of life infrastructure and environment and caused by natural and man-made hazards. But before going further in details of disasters and its assessment, it is important to note vulnerability and exposure in terms of hazard and disasters. Exposure is basically the situation of life, property and various tangible and intangible asset in and hazard-prone areas. It can vary depending upon different environmental settings and demographic social parameters. While a vulnerability is a situation that explains how susceptible a section of society is depending upon physical, social, economic and environmental features that can aggravate the degree of loss and damage. Basically, it's a situation wherein the more fragile the environment, the weaker the socio-economic demographic status, the higher is the vulnerability. For instance society with the least awareness of hazards, poor infrastructure lack of preparedness measures an increase the degree of a disaster making the area more vulnerable. It is basically the ability and capacity to withstand disasters.

Hence, a disaster is an actual loss of human lives, property, resources, socio-cultural structure and environmental damage in an area. It is a direct and indirect outcome of hazards. Disaster presents the actual status of society disrupting the normal functions of society wherein it becomes difficult for the communities to deal with it. Disasters on the basis of time and interval of occurrence could be immediate, rapid, slow and sometimes sudden eruption (Fig.6.1).

World over there is an increase in the prevalence of disasters in terms of intensity, frequency and magnitude across the globe. With increasing population globally, human occupancy has reached the areas that are ecologically, tectonically and strategically prone to the wrath of nature. Infrastructural setup and the over exploitation of natural resources for economic gains in unscientific and unsustainable ways have gone beyond the critical limit of earth's tolerance. Human interference has gone deeper and closer to the naturally sensitive areas like higher altitude areas near the glaciers and glacial lake, riverine floodplains prone to floods, coastal plains prone to cyclones and tides and areas prone to flash floods and landslides. These situation have increased the amount of loss and destruction caused by disasters.

Glacial lake outburst floods, a natural hazard, are associated with high altitude mountain terrain characterized by scanty vegetation and fauna, widespread glaciers and devoid of large settlements.

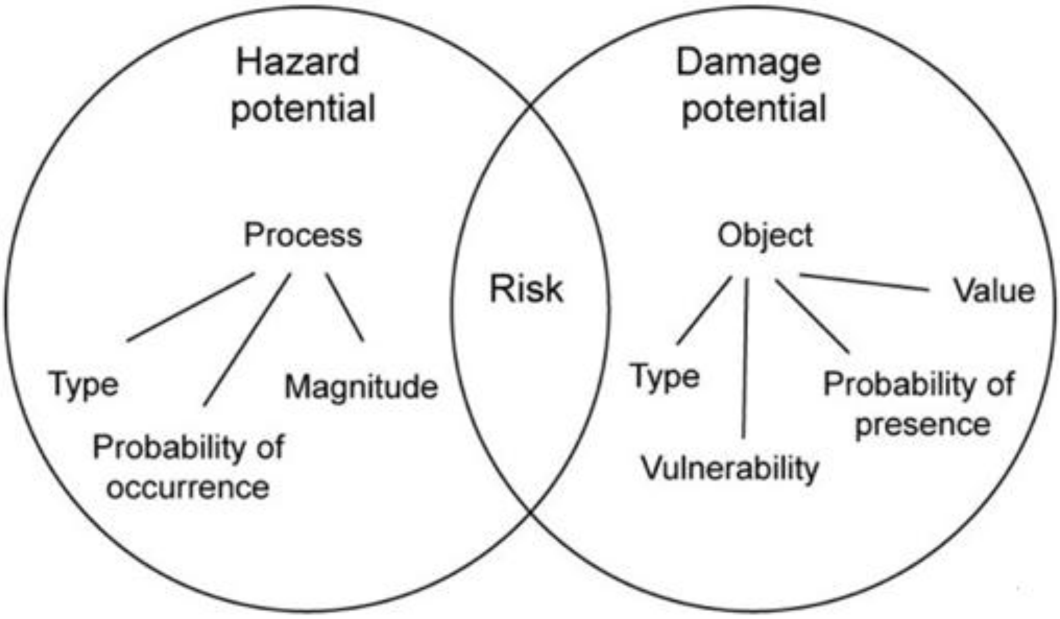



**Fig 6.1 Hazard and Damage Potential.**

## 6.4 DATA SETS

There are 5 thematic layers used as a raw material or base maps for the final creation of the vulnerability assessment map. The data sets used are:

- ALOS PALSER (DEM) with 12.5 meters for the study area collected from the USGS.
- Flood inundation map prepared by HEC-RAS software as one of the layer.
- LANDSAT 8 image to create LULC for the catchment area.
- Primary data from the field to estimate economic loss within the inundated area.

## 6.5 METHODOLOGY

- DEM is used to extract the elevation map, slope map, and the river and streams of the region.
- In the present study, Weightages Overlay Method (WOM) is used with the help of multi-criteria analysis (MCA) for vulnerability assessment of within the Sissu watershed.
- Factor score of 40%, 30%, 15%, 15% to flood inundation map, LULC map, stream buffer, and elevation of the catchment area.
- Class 1-5 with 1 least vulnerable and 5 max vulnerable.
- Simple multiplication and addition to calculate total monetary loss of each economic sector and its conversion in present-day USD.

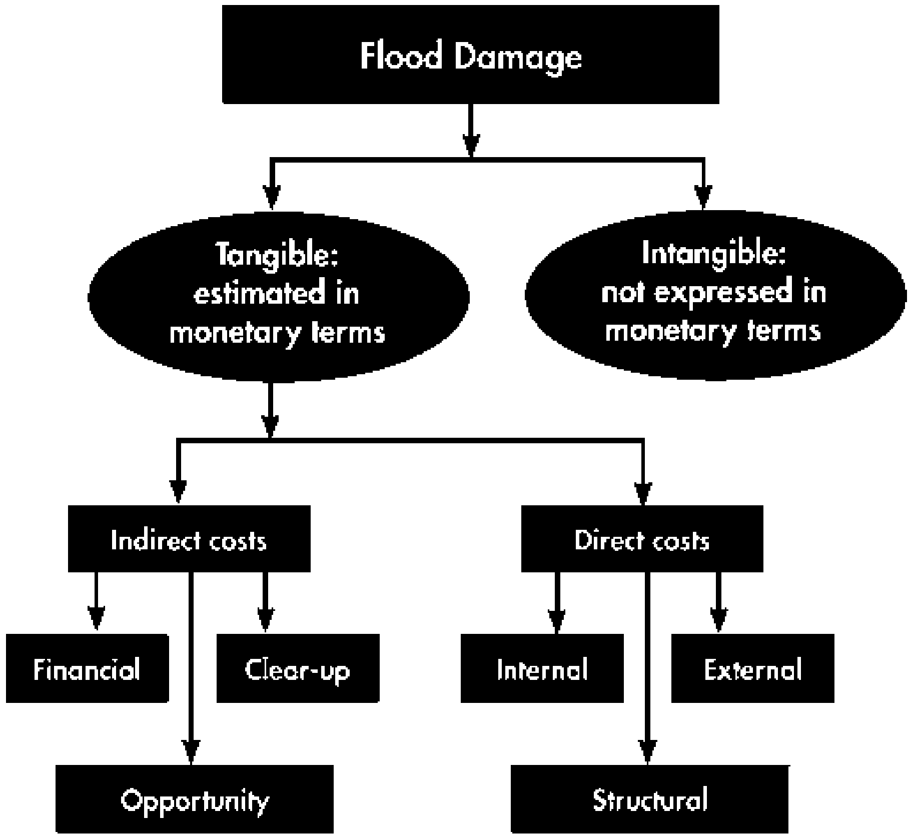



**Fig.6.2 Potential Loss in case of GLOF.**

## 6.6 RESULTS AND ANALYSIS

High altitude terrain is a highly vulnerable topography. As Glacial Hazards have the maximum likelihood of occurrence over here. And glacial hazards are an extremely unpredictable natural hazard with huge destruction potential. Due to difficult terrain, the least movement and accessibility, predicting and foreseeing any upcoming disaster is impossible. Therefore, scientific knowledge making use of various hydrodynamic software precise flood simulation should be prepared on regular basis. The prepared flood inundation maps can provide an information on the extent and magnitude of the GLOF event. This also acts as a base map to obtain information on various aspects of loss and destruction such as a number of human lives, physical and economic infrastructure to get damaged at the same time to work on the psychological and social-cultural loss. This study is directed towards connecting the scientific and local indigenous knowledge of the people in the alpine regions. Indigenous practices aligned to the tune of nature and environment help them from the devastating impacts of natural calamities. No socio-cultural economic and psychological domain will be out of danger.

Therefore, here flood inundation map prepared for the Sissu watershed is our base for further study. The flood inundation map covers the entire region that is likely to get damaged in case of the probable GLOF disaster. This study is also an attempt to understand the probable impacts of changing environmental conditions on social lives as well as on agriculture and other means of livelihood within the flood inundation area.

Sissu, also known as Khwaling is one of the largest and densely populated town of Lahaul region. It is connected with Manali through a recently constructed Atal tunnel. It is one of the important tourist destination within Himachal Pradesh. Shashin, features a famous local deity called Ghepan/Ghepang or Lord Gyephang within the region. Gyephang Goh mountain is known as after him. It's a centre for the nearby villages of Ropsang-Khangser-Gyungling, Gomathang, Yangling, Jagdang, Sarkhang, Shurthang and Labrang. Due to the close proximity of Sissu fron the North Portal of the Rohtang tunnel, it maintains its connectivity throughout the year. It's a well-liked tourist place within the area. The region is additionally more important because it forms a connecting link between Ladakh with remaining state as highway passes through a bridge in Sissu town. All of these factors make Sissu a crucial region. At the same dynamic and expanding Sissu lake make the region all the more fragile and vulnerable. Therefore, to keep the lives of people in so many associated villages going and maintaining connect between Ladakh and rest of the country, Sissu regions needs to be protected.

The Sissu Lake gives way to the Sissu nalah which is an important source of life to entire Sissu and Shashin villages. This Sissu nalah comes out from a pro-glacial lake fed through the Gepang Goh glacier. The studies through the previous chapter depicts that, there is an increase in size and volume of Sissu glacial and decrease in the area of glaciers within the watershed. Continuous increase has put a worrisome picture of a probable event of Glacial Lake outburst floods in near future. The impact area through flood inundation depicts that there is a large chunk of Sissu village under threat in terms of lives and property (Fig 6.1 and 6.2).

| | |
|---|---|
| MEN | 98 |
| WOMEN | 90 |
| CHILDREN | 80 |
| ELDERS | 11 |

**Table 6.1 Lives under threat in case of GLOF event.**

There are 279 people that are at the risk of losing their lives in the case of GLOF out of which 91 make the dependent population. There are 98 active male working population that are a part of the active and working economy. While there is a young population of 80 children. It is even a greater loss because these young kids are a demographic dividend that would play a major role in shaping and forming a developed economy. These demographic dividends are the future of a young nation in making like India. In terms of physical infrastructure also the loss is huge. There are 25 houses in total that might get demolished. There is a vast stretch of agriculture that makes an important means of sustenance for the agrarian population. Along with these privately owned units, there are many public infrastructures built from the money of the consolidated fund of the state some of which are critical infrastructures. These critical infrastructures are one government school, one government hospital, one Public Works Department Office. There is also an important bridge connecting the Sissu town with rest of the state. Highway passing through the town undergoes heavy traffic flow on daily basis. There are close to 3000 public and private vehicles passing through this highway. It is an important source of constant economic supplies for the general public and defense forces stationed at Ladakh and other regions of Lahaul. There is going to be close to 4 kilometers of the total length of the road likely to get damaged. This road is such an important link for the survival of the Himalayan inhabitants that if at all this roads gets damaged, the entire area will be devastated. The whole Himalayan economy and society will come to standstill. In the case of GLOF disaster, even the rehabilitation and evacuation process will also get impossible. The Sissu region also has a helipad that is used to airlift the patients during winters at the same time for the constant supply of essentials during winters when the roadways are blocked in winters.

| | |
|---|---|
| No of houses 25 | No of school 1 |
| No of hospital 1 | Other building pwds |
| Area under agricultural 222 bigha | Area under forests 48 hec |
| Pasture 4000 bigha | Area of helipad 5400 sq meter |
| No of Bridge and Dams 1 | Length of Highways 4 km |
| No of vehicles passing per day | average 3000 per day |

**Table 6.2 Total Area, Number and Type of Infrastructure under Threat In Case Of GLOF Event.**

If we further calculate the total figures of all the infrastructures loss in terms of monetary value, it is huge which stands close to 3,430,748 USD cumulatively from construction, agriculture, economic and social infrastructure. In the retail sector of the economy that includes total construction of a house. It includes the labor costs engaged during the building up of a house, costs of a single brick multiplying the total number of bricks required, cost of one kg of Cement multiplying it to the total cement quantity required. It further includes the cost of total iron rods used. All these calculated values is the construction costs of a standard 1000 s feet house in the region. The probable loss figure in this case is 200100 USD. In the case of agriculture, cauliflower, peas, potato, corn wheat, green leafy vegetables are the major crops grown. The region is a closely knitted society with limited economic exports and import. Therefore, most of the produce is used for self-consumption with limited exports. The net loss in agriculture is the present market price of one unit of the individual crops and multiplying it to the total production in the area under cultivation of that particular crop. In this case, the total loss figure is 17083 USD. In case of the personal loss that is the individual household monetary loss, are the values of all the material things cumulatively. This loss stands at 63565 combined with the loss of private homestays, community-recreation Centre and a local temple (Table 6.3).

| Category | Monetary value(in USD) |
|---|---|
| Reconstruction cost of house | 200100 |
| Agriculture(export quantity self-consumption) | 17083 |
| Loss of personal assets<br>Tourism homestays, temples, Sissu recreation Centre | 63565 |
| Critical Infrastructure | 3150000 |

**Table 6.3 Monetary Loss in Case of GLOF event covered under Flood Inundation (2020)**

Now, these are the direct damage values that can be quantified. Apart from this, there are latent costs that cannot be quantified. For instance, when a house of the villager gets demolished, it destroys all the material articles inside. Once the normalcy is restored and the family starts its life all over again. The first task is to construct a new house. Once the house gets constructed, they need to buy all the essential articles. Now the effective economic loss gets greater because if we assume that the family had spent around 5 lakhs for the construction of a house. If the flood occurs, and the house gets demolished there would be a loss of 5 lakhs. In the present age adding the inflationary costs, the effective loss would be even more. But the greater latent and additional loss is repetitive use of money for the same purpose. Meaning thereby, the additional money used for the reconstruction of the household could have alternatively been used for academic, economic or any other socio-cultural growth and development of the family. The money could have also been used alternatively for the development and realization of demographic dividends providing various future opportunities to them. Therefore, this loss remains uncalculated. Land use and land cover classification of the Sissu watershed demarcates a narrow zone with a cluster of settlement and economic activities. From 1975 to 2015, there is a significant increase in the area under settlement, agriculture and a decrease of glaciers (Fig. 6.4). There is a continuous increase in the population and expansion of economic activities in the higher areas. There seems to be an encroachment of mankind into more sensitive and vulnerable higher areas. In the wake of this, there needs to make a classification of the whole area into various classes or zones with varying degree of loss and impact. The whole watershed has been divided into 5 zones with 1 being the highest and 1 being the lowest in terms of degrees of loss (Fig. 6.3). Zone 1 includes settlements, and all the critical public and private infrastructures. Water draining down from the stream reaches near the Sissu bridge area, due to the sudden break in gradient flood water distributes laterally and horizontally within the region. This horizontal spread of water in huge volume engulfs the whole area and its lives and properties. Zone 2 covers the area under pastures for cattle grazing and a few plantation areas. Loss of this region will lead to the permanent loss of the grazing fields that is food for the livestock. Cattle are an important component of Alpine societies. Zone 3 is basically a buffer region around the Sissu nalah. Zone 4 and zone 5 are the areas of least concern. Apart from this, the area will also undergo geophysical modifications. The impact of surging water will uproot the trees from their roots off. When the trees get uprooted, it impacts the weathering and soil formation processes. This can accelerate soil erosion too. Eventually, in due course of time, it can affect soil water moisture holding capacity, ground water discharge, soil fertility and stability of the top soil layer. The cohesive strength of the rocks and soil layer also gets impacted. All of these modify and re-shape the overall physical health of the region.

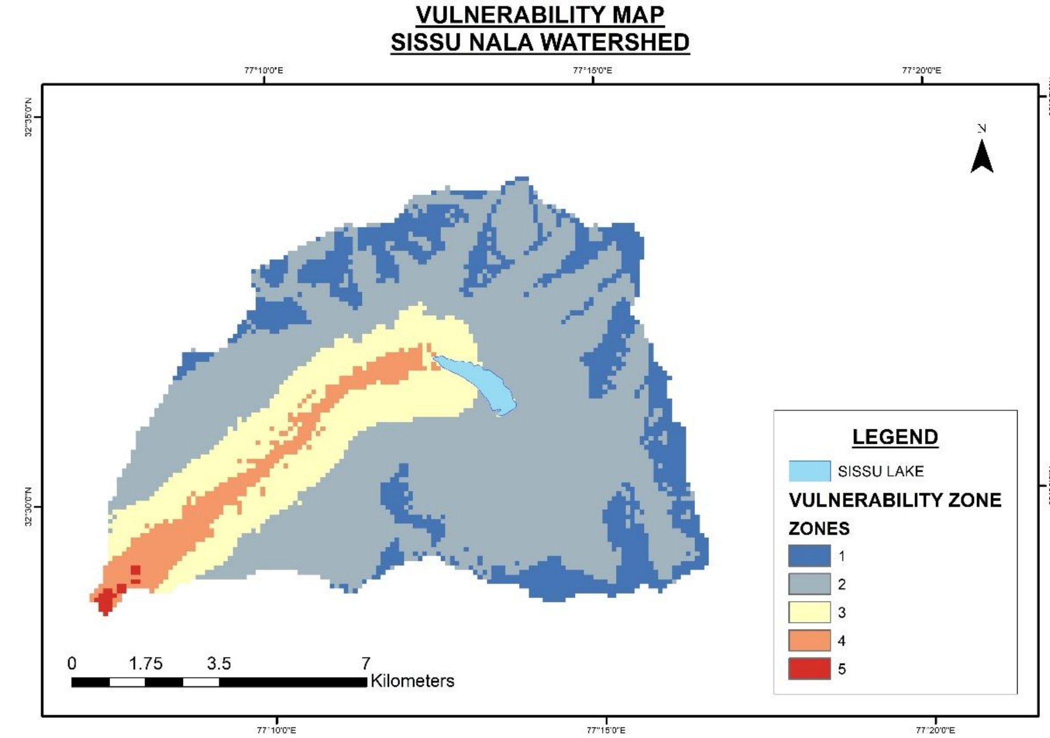



**Fig.6.3 Vulnerability Map with Hazard Zones**

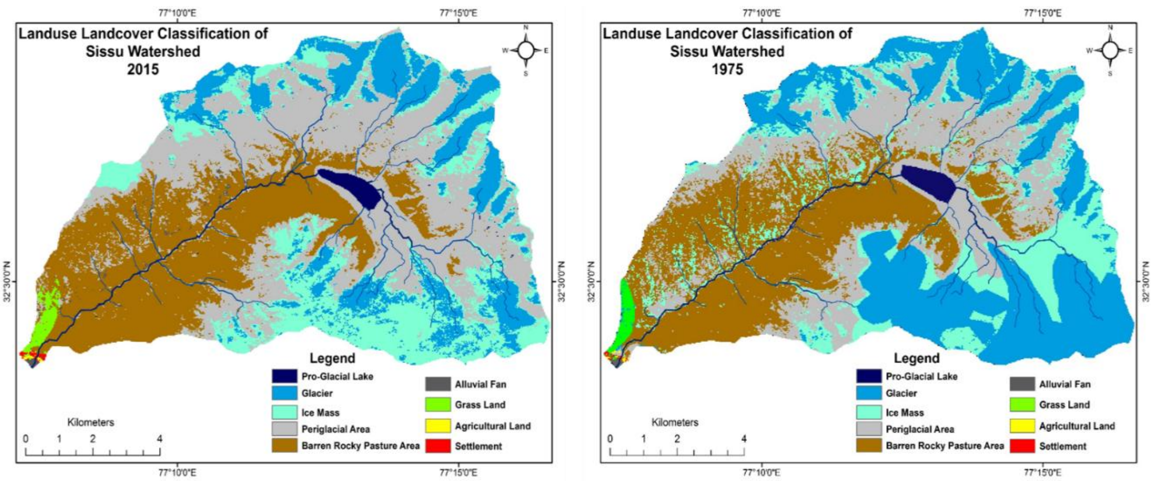



**Fig.6.4 Land Use Land Cover Classification of Sissu for 1975, 2015**

Agriculture is the major economic source for the people in the region. Maximum area under cultivation is under potatoes, peas, cabbages, turnips, and cauliflowers. However, farmers are cultivating other traditional crops like Manu, Kuth, Rajma, and Barley in limited quantities for subsistence because of the inability to fetch the higher market price and comparatively longer growing time of these grains. The region has observed a complete shift from the production of Barley to other crops, while in other areas, there has been a drastic reduction in production. Contemporarily many farmers cultivate vegetables in apple orchards. The region is getting diversified in terms of traditional cropping as well as commercial cropping with a wider array of crops grown. This may be attributed to the role of roadways and ease of accessibility to the villages.

Since high altitudes are characterized by short growing seasons, farmers have a high dependency on climate for sowing and harvesting times as crops are sensitive to frost and temperature values beyond the threshold. A climatic study that necessarily involves the hard knowledge of the climatic parameters can significantly benefit from the soft expertise derived from the experience of the society that resides in the region. Hence, the relationship between agriculture and climate is intricately connected. Variability in snowfall, temperature, and rainfall has a great degree of impact on the livelihood of the population.

According to natives of the village during field visits: "*higher snowfall benefits the agriculture because it provides humidity to the soil at the same hampers the growth of wild grasses in the fields".* But in the opposing scenario, the framers manage and utilize water from the Kuhls for irrigation. Some others said, "*On time and sufficient precipitation boosts agriculture and horticulture leading to bumper production of crops.*" This suggests Kuhls to be an important component of the agriculture in the upper reaches. Blocking of Kuhls by the boulders and other sediments brought down by the Sissu Nalah or complete breaking off the Kuhls will have a severe damaging impact on agriculture. Agriculture will get completely damaged. Kuhl is an important local human adaptation living in the higher altitudes used for drinking purposes too along with irrigation. It is a synonym of man's interaction with the region.

**Plate 32:  Grazing fields and the Helipad in the Sissu region.**


**Plate 33. Photographs a (approximately 75 years old) and b (2017) shows no significant retreat in the glaciers (c) old Apple trees village approximately 60-70-year-old; (d) apple orchard planted in 2000 in the village.**

**Plate 34: Seasonal Snowfall and its impact on Agriculture**

Within agriculture, there are several seasonal migrants who come to these areas from the neighboring villages and some from even Nepal too. Their families are also the sufferer. Apart from agriculture, tourism is also a major economic sector. There are several homestays, hotels, tourists, resorts. There are hundreds of tourist coming in here seasonally. In this sector, it’s not just the locals but also the several migrants involved too. They work at local dhabas, or as porters. There are many tourist guides too. Along with this, there is a complex network of transportation that is intricately linked with the tourism sector. Because tourism has a multiplier effect on society. In case of the disaster tourism and allied activities will become standstill. Some of the important physical public-private and critical under threat in the case of GLOF is presented below through plates.

**Plate 35: Gepang Nath Temple a cultural infrastructure (a), primary school public infrastruture(b)**

**Plate 36: Primary Health Care Centre public infrastructure (a) and a private infrastructure (b)**


**Plate 37: Government Hospital (a) and a Co-Operative Bank (b)**


**Plate 38: Highway passing through Sissu town (a) a hotel and a resort (b)**

**Plate 39: Sissu Nalah draining down from Sissu Slacial Lake (a) Construction activities at the periphery of Sissu town (b)**

There are other greater losses that cannot be quantified. These are a social, cultural, physiological and psychological losses. Disasters leave an everlasting mental and emotional trauma on the people. It takes several years for them to come out of this trauma. Loss in their mental and emotional health diminishes their work potential. It takes several years for the people to heal from the loss of their loved ones and their houses. This can make many people mentally unstable. Their coping mechanism can push many of them into anti-social practices. This further affects their physiological health too. Yong kids who would spend their childhood in school spent their formative years in the recovery from the disasters.

This also has negative consequences on the socio-cultural lives. Inter-personal relationships get affected. Most negatively affected are the dependent population because if the earning member of the family dies, it becomes and an irreparable loss to them. These dependent populations include the children, elderly and women population. This dependent population particularly women bear the repercussions of the disasters silently. Culturally also a society gets impaired. Destruction of the age old temples, community cultural and recreational centers devoid the future generations of the rich cultural heritage of their ancestors. These are the unidentified unspoken loss that affects the quality richness and diversity of a human lives.

## 6.7 CONCLUSION

As discussed in the chapter, the deadly impact of disasters are inevitable in the case of GLOF. Therefore, hazard assessment and flood simulations to be applied on the impact area is a must. In the wake of the growth and development of the economy, diversification of the economy, multiplication of the infrastructures to cater to the needs of the growing population, alpine regions are not inaccessible. People are penetrating into the higher altitudes to realize untapped immense resource potential. Human beings have started to break the mountain barriers. They are constructing new infrastructure projects at the higher altitudes now. To fulfill the goal of sustainable development, nations are switching to green energy sources. For this purpose, the focus is now on the hydro-electricity instead of thermal energy which is one of the major source of carbon emission. Presence of perineal water supply, the Himalayan region is a rich source of hydroelectricity. Therefore, there is a goal of setting up of a chain of several small and large hydel power projects. For this purpose, there is going to use of dynamite breaking off boulders from the mountains to construct dams and reservoirs. There are further new roads, bridges and tunnels are also proposed to get constructed. All this would definitely disturb the natural homeostatic balance of the mountainous terrain.

Apart from this, of late Himalayan regions have become a major source of tourism. It has become another major economic source. Adventure tourism such as skiing, hiking or a simple recreational tourism for rejuvenation purposes, the Himalayan states are now hotspots. Policymakers are putting a major thrust on the development of the Himalayan states. For many growth and development simply means the construction of infrastructures. But all this attempt will be futile if it is not done to the tune of nature's balance. Our elders have rightly said that prevention is better than cure. Instead of diverting the government exchequer on rebuilding the society and rehabilitating the population, it is better to have a development model which is aligned to maintain the balance between human development and nature conservation. Because in such averse scenario, there is no turning back to rectify human errors or blame Mother Nature. Therefore, there is a pressing need for hazard assessment. This will help in hazard preparedness as well. Vulnerable sections of the society and the physical infrastructure at the risk should be identified to be taken care of. There is a need to generate awareness among the locals, policymakers, NGO's, governmental originations and all the other stakeholders involved. There is a need to encourage community partnership. But before all this, the first and foremost task is to prepare hazard zonation mapping by the scientific community using the available data sets. Based on these outcomes, preparatory and mitigation measures could be suggested.

Therefore, there is a need to understand the dynamics of glaciers and glacial lakes amidst the hue and cry of climatic changes and global warming. Once the dynamic glaciers and vulnerable lakes are identified, individual potentially damaging lakes could be studied in details. There can be monitoring stations installed at such lakes. Remote sensing satellite data sets and preliminary filed investigations can provide precise information to prevent the eminent danger of GLOF in future. But to develop mitigation plans and policy measures, identification of the hazard potential and its likelihood occurrence should be continuous monitoring and assessment process. Once the causes, impact, duration and tentative damaging potential of a hazard is known, quick and accurate measures to contain and reduce the negative externalities of the disaster can be put forward at the local level. It will be a crucial step to reduce the damage to a minimum. This requires strenuous and collaborative efforts from different governments together because the glacial disaster produce trans-boundary impacts globally (Reynolds & Richardson, 2000). Of late negative consequences of the climatic fluctuations are more evident on the Himalayan region for its recent orogeny. This setup has further been disturbed by human influence and climatic variability. Though the glacial born disasters cannot be predicted and contained but successful monitoring can surely give preparedness time to reduce the damage. This required sustained efforts from policymakers and will to tackle it by sharing data sets with other nations. There is an imperative need for accurate, precise, and continuous monitoring of the glaciers and glacial lakes to formulate risk-reducing measures. The variable snowfall, rainfall and cloud-bursts, along with increasing in snow & glacier melt-waters challenge the existence of many settlements in the mountain regions.

# CHAPTER 7

# SUMMARY AND CONCLUSIONS

## 7.1 THE HIMALAYAN SOCIETY

The Himalayan society is a region of absolute dependence on the natural surroundings for the survival of mankind. It is a region of complex and a delicate relationship between the man and the environment. Nature looks after the needs and requirements of the mankind. Previously glaciated valleys which are devoid of glaciers now are inhabited by the villagers. With the passage of time and development processes, it became a cohesive mutually inclusive societies with array of knowledge passing through generations. These local knowledge, traditions and practices passing though different generations have helped in the evolution and betterment of the society. All these adaptations define the micro-regional settings of an area. Mountain terrain being climatologically harsh, geologically unstable, ecologically sensitive and economically vulnerable are challenging to live for the inhabitants. Their settlement patterns, housing types, dietary choices, food preferences, economic set up, cultural ethos all are the bi-products of the physiography and climate of the Alpine regions. Hence, geography and demography both are a vulnerable sections in the Himalayan region. In the present context, there is a hue and cry of climatic changes and global warming across the globe. Amidst the climatic fluctuations, it is perceived that the mountain glaciers are receding .There climatic fluctuations will become the precursor for natural disasters. Such receding glaciers are a factor responsible for the formation and increase in size and volume of glacial lakes at higher altitudes. These glacial lakes lead to incidences of GLOF in unforeseen scenario when the increase in the volume and size crosses the carrying capacity. This scenario is getting threatening with the Himalayan region. This study, appertained in seven chapters begins with gives a brief introduction of the topic of further study, objectives, data sets and the methodologies to be used in further. It is aimed at understanding the dynamics of GLOF in Lahaul & Spiti region in relation to the dynamics of the glaciers. Next chapter deals with a brief analysis of the study area. It introduces the geo-physical setting, climatic and social aspects of the region. This study aims to understand and analyze the dynamic interlinkages between glaciers and glacial lakes. There is also an attempt to analyze the increasing threat of GLOF amidst the fluctuating atmospheric parameters.

## 7.2 GLACIER AND GLACIAL LAKE INVENTORY

Number, types and distribution of glaciers and glacial lakes are analyzed in detail. There are 2189 glaciers in Himachal Pradesh. Within Himachal Pradesh, Chenab basin which covers Lahaul & Spiti has maximum concentration of the glaciers while the least in Yamuna basin. There is change in the extent and total area of glaciers in different basin where Beas basin shows maximum loss of glaciers. Chenab basin has varied glacier types morphologically. Within Chenab basin, slope, aspects and angle has an influence on the glacier dynamics locally. There are 63 glacial lakes identified in Lahaul & Spiti. Out of which, 17 are moraine-dammed, 16 pro-glacial lakes and 16 supra-glacial lakes each in Lahaul & Spiti. While there are only 2 valley glacial lakes and 11 blocked glacial lake. Attitudinally, 50% of the glacial lakes are distribution between the range of 4000 to 5500 meters above mean sea level. There are only 3% glacial lakes above 5500 meters and below 4000 meters mean sea level each. In terms of area, there are 30 glacial lakes between the range of 0.05 -0.01 $km^2$, and only one lake with an area of 1 sq. km. There are10 glacial lakes are in range of 0.05 to 0.01 $km^2$, and 10 with less than 0.001 $km^2$. Decreasing size of glacial lakes with increasing altitude again exhibits the role of topographic control. Because at steep slope and high gradient, there is less deposition and accumulation of water due to absence of flat and wide area to form a depression or an impoundment. This restricts the accumulation of lake water and leads to downward movement to the valley in the form of numerous seasonal streams. While at the lower altitude, higher run-off also restrict the formation of glacial lakes. Therefore, there is wide range of distribution of glacial lakes in terms of size, type, altitude and other such characteristics.

## 7.3 VULNERABALE GLACIAL LAKES

Disaster of GLOF depends on the stability of the glacial lakes. Not all glacial lakes lead to GLOF, nor do all the lake remain stable throughout the geological time period. Climatic, lithological, geological, tectonic anthropogenic and other such environmental factors make the lakes more vulnerable. But the most important factor responsible for the dynamism of the lake is the conditions of the parent or feeder glacier. For this purpose, ELA becomes an important aspect that depict the glacial activity. Along with the geomorphic and other such parameters of the lakes, lake surface temperature is also an important factor in lake dynamism. Lake surface temperature aggravates the melting of the glacier and hence important factor to evaluate lake dynamics. Temperature basically has a cascading effect on lake reactions. Therefore, it is also imperative to analyze lake surface temperature within the watershed for further assessment. Land Surface Temperature (LST) is a useful proxy measure in data-scarce reaches of the mountainous environment to evaluate lake dynamics.

The LST pattern in Chandra basin of Lahaul & Spiti is notably different from the rest of the basins due to topographic and orographic gradient. July and August are the months which exhibit the highest basin average LST, whereas January and February are the coldest months of the year. The highest basin average LST in the summer months was noticed in July 2013 with a value of 10.64°C ± 0.53°C followed by August 2005 with a value of 9.76°C ± 0.49°C and August 2014 with a value of 9.62°C ± 0.48°C. Lowest summer temperatures were exhibited in August 2010 with a value of 6.57°C ± 0.33°C. The coldest basin average LST in the winter months was noticed in January 2008 with a value of -19.95°C ± 1.00°C, followed by January 2011 and 2012 with values -18.99°C ± 0.95°C and 18.67°C ± 0.93°C respectively. The Chenab Basin houses the maximum number of large glaciers (exceeding 10 sq km) while the largest in the basin include Bara Shigri and the Samudra Tapu glaciers. The ratio for the estimation of ELA has been considered 0.48. The maximum average Equilibrium Line Altitude in the glaciers in the year 2000 was noted to be 5576 m while the lowest was noted at 4641 meters AMSL respectively. In the year 2016, the highest estimated ELA was 5541 meters, and the lowest at 4663 AMSL. The median value of change in ELA is 0 which means that most of the bigger glaciers in the valley are stable according to their mass balance. However, the maximum retreat value of 22 meters has also been observed for glacier which has shown a retreat of 0.38 $km^2$. Sissu and Samudra Tapu Glacial lakes are the most vulnerable lakes, they shown an increase in the area and volume both. There is a marked decrease in glacier area as well within Sissu watershed. Sissu is a deep pro-glacial moraine dammed lake at a higher altitude while Samudra Tapu glacial lake in a shallow lake in flat wide valley. These two are expanding lakes. Glaciers within the watershed have undergone lost mass balance vulnerable analyzed here. From 1972 till 2020, there has been an increase in the lake volume, particularly in Sissu lake that has got deeper. It has been expanding horizontally and laterally towards the snout of the glacier. Samudra tapu lake is also expanding laterally within the watershed. Thus, expanding the lake area.

## 7.4 FLOOD INUNDATION MAPPING

Disaster management and hazard assessment are twin objectives necessary for the sustainable human development. For this purpose, flood simulation modelling is to be done. Barren, deserted and virgin mountainous terrain are now under the impact of intense economic activities and evolving fast. The Himalayan states have become an important source region to generate hydroelectricity. More hydel power projects are proposed in such areas. Rising numbers of tourist hotspots have led to increase in density of transportation as well. Fallow lands are fast diverting towards the agricultural activities. In the wake of all this, inundation mapping is done to estimate the area under damage in case of a GLOF, as such conditioned are witnessed in case of Sissu watershed. HEC-RAS 1D model has been used for this due to limited availability of filed data sets. The results of the HEC-RAS 1D model shows that the maximum peak discharge is 46820 cubic meter per second and the total water volume estimated is 31065556 $km^2$, while the total inundated area is 3.04 $km^2$. Results of the flood inundation mapping also depict that the maximum flow depth ranges upto 41.38 meters. As per the simulated map, flow depth of more than 20 meters could exist for 3.5 kilometers for the Sissu nala before it intersects the Leh-Ladakh Highway. The flow depth increases beyond 25 meters around 4.5 kilometers upstream from the Leh-Ladakh highway for about 1 kilometers; and then again briefly for a few hundred meters around 6km upstream and 7 kilometers upstream. The flow velocity ranges from 1.87 m/s to 47 m/s. The flow velocity is the highest in the upstream region where the valley is narrowest and the slope is steep. Such a flow extends for approximately 2.5 kilometers. The flow velocity is least near the helipad- 1.87 m/s. Velocity at mountainous terrain is a slope and elevation dependent indicator. Therefore, higher the elevation and slope, higher would be velocity. As per the simulated map, the water inundates almost 20 percent of Sissu village but the major part of Shashin village remains out of the inundated area. Cultural infrastructure of Shashin village like Gepang Nath temple associated with identity of the village remains unaffected. 20 percent of settlements of Sissu are likely to get inundated. Helipad, hydel power projects, national highway connecting Manali to Leh and connecting bridge on Sissu are some of the critical infrastructure likely to get destroyed by the outburst as shown by the flood inundation results. This flood will have immediate and long term negative impacts. The immediate impact will be loss of human lives, cattle, destruction of infrastructures including houses, transportation lines, dams, bridges, power projects etc. While the far-sighted impacts will be on the overall health of geo-physical environment. Debris spread over the agricultural fields will hamper the agricultural practices. Direct uprooting of trees and pastures will affect the soil erosional and soil moisture holding capacity. This in turn can affect the fertility of soil. Sudden gushing water can lead to slope failure. This slope failure can have an impact on the stability of the surface. At the same time, falling off and deposition of boulders and gravels can lead to permanent shifting of the stream course. It could also cause blocking up of the Kuhls. Emptying of the glacial lakes, will eventually affect the supply of waters thought Kuhls to downstream regions. This will hamper the perennial availability of water. In due course of time, overall configuration and land use land cover practices of the region will get altered. Samudra Tapu Lake is less likely to cause damage because it's a shallow lake holding less amount of water. The valley region is also wide and flat. Therefore, flow of water will spread out laterally. Huge volume trapped in narrow path from a high altitude, flows more vigorously at a high velocity. This causes the maximum damage.

## 7.5 DAMAGE ASSESSMENT

Hazard is a natural process with a potential to causes loss of lives, injury and health damage, infrastructure damage and other social economic and environmental damage .Hazards could be a single event or chain of events each with their own characteristics and process. But a disaster is an actual event causing the real havoc on the earth taking lives and destroying properties worth millions. Hazard is an event that might or might not lead to disasters. It's the risk and vulnerability that decides the extent, magnitude, degree and intensity of destruction. Higher the risk and vulnerability of population, bigger is the disaster. And this risk and vulnerability of the population is an outcome of socio-economic, cultural, demographic and other such environmental factors. Segment of population which is more vulnerable has the higher risk of loss in case of disasters. For instance society with least awareness of hazards, poor infrastructure, lack of preparedness measures increase the degree of disaster making the area more vulnerable. It is basically the ability and capacity to withstand disasters. Since the high altitude environment is a vulnerable and a sensitive environment zone, lives and property are at a greater risk. Damage assessment in case of disasters could be categorized as temporary and permanent and direct and indirect. Area under flood inundation in the Sissu watershed for the period 2020 is huge which will definitely has the possibility to get bigger in the upcoming years if the present rate of increase in size of the lakes and the development activities continue anabetted. Since this is a compact and densely population region, greater population is at risk. In terms of properties, critical infrastructures viz dams, bridges, transportation links, hospitals, government rest houses etc. are under threat. Damage to Sissu Bridge will cut off critical highway to Ladakh. This route is also used for deployment of defense forces. This will also severe the supply of daily essentials and rehabilitation works for the victims. The long term and indirect damage can impair the victims off the mental, emotional and psychological stability. Mental and emotional can make them more sensitive, vulnerable and fragile. It can break their spirits for lifetime. It can make healing process worse.

## 7.6 CONCLUSION

Climatic variability and global warming are a topic of discussion in the 21$^{st}$ century. These are considered a factor responsible for dynamism of glaciers because glaciers are sensitive to even slight changes in the atmosphere. Indiscriminate use of non-renewable and polluting resources also has its damaging consequences on the atmospheric health. Scientific community and researchers have been highlighting this aspect in several studies. But still human needs for better life have been increasing substantially. Therefore, there is a quest for sustainable and environment friendly alternative new solutions. This compelled them to explore uninhabited virgin mountain regions. Mountainous areas are no more devoid of the human interventions. Encroachment by the reckless human activities are destroying the mountainous topography. Environment has a fixed carrying capacity and a definite natural homeostatic balance. Uncheck and unprecedented human actions are on the verge of destroying these areas completely. If it goes beyond the regenerating capacity of the nature, it will be impossible to control the unimaginable wrath of the nature. Therefore, there is need to protect the Himalayan regions.

## 7.7 SUGGESTED SOLUTIONS

There are two kinds of measures to control the damage caused by any disasters. This can be prevention and regulation measures. Some of the measures of preventions are listed below:

1. Avoiding setting up of infrastructures with high installation costs within the probable flood inundation areas.
2. Avoiding construction activities in the geologically unstable and active tectonic regions.
3. Avoiding construction activities or using of dynamites in the vicinity of the glacial lakes.
4. Restricting tourism at the higher altitudes.
5. Regulating the movement of people, settlement and cluster of economic activities in the flood inundated areas.
6. Constructing alternative routes to avoid heavy traffic flow particularly in the case of Sissu Bridge.

While the regulation measures to dedicated towards the glaciers and glacial lakes are as follows:

1. Precise and accurate identification of the Potentially Dangerous Glacial Lakes and the detailed analysis of their source glaciers.
2. Regular real time monitoring of such lakes and changes in its volume and area through filed investigations.
3. Application of 2D and 3D hydrodynamic scientific models using multidimensional field data sets to tabulate hypothetical flood event and prepare flood inundation maps.
4. Prepare suitable plan of actions identifying the vulnerable sections within the flood inundation area.
5. Artificial measures of dewatering of the lakes.
6. Installation of pipes and construction of narrow channels to lower down the increasing volume of the glacial lakes.

7. Construction small reservoirs to divert the lake water supply.

8. Constructing narrow openings within the crests to allow continuous slow seepage of water.

Apart from this, on time relief, rehabilitation and evacuation measures should also be kept handy to minimize the destruction as much as possible. Small regions, especially in the non-homogenous mountainous regions, are very critically influenced by weather and physiographic parameters that need to be identified within the deep ecosystem. There is a need to understand the cumulative change in society as a result of change in the environmental factors. Indigenous people's involvement would help miles in understanding the behavior of nature due to their close ties for their livelihoods. Local knowledge needs to be acknowledged to formulate mitigation strategies in case of any distress. The mitigation strategies would include better coordination between science, technology, management, communities, and policy-making.

## 7.8 FUTURE RESEARCH

This study suggests that standard parameters could be set for future studies related to investigating the response of glaciers to climatic change in the Himalayan region. Future studies, having glaciers of similar characteristics, with similar data sets, and similar methods would be helpful to understand the response of the glaciers to climatic change across the region and robust regional synthesis could be established. On part of the regional concern, the study further suggests that regular field based monitoring of the glaciers are needed. As it is evident that glacial lakes could be dangerous causing abrupt deglaciation, future policies should focus to find out the practical solutions to tackle the same. Considering the nature of climatic change in the region, policies also should focus on the sectors which are sensitive to the change in minimum temperature. To understand the paleo-glaciations and related environments, more geo-chronological studies are required not only in the Himachal Pradesh but also across the Himalayan region. The enhanced geo-chronological studies on the glaciers in Sikkim would be helpful to understand the past dynamics of the Indian summer monsoon which eventually would be helpful to predict the future for better planning purposes.

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# ANNEXURES

# GLACIER LAKE SUMMARY

| FID | Name | Area (in sq. km) | Latitude | Longitude | Mean altitude above MSL (in meters) | code | orient |
|---|---|---|---|---|---|---|---|
| 46 | 80 | 0.001069 | 32.67181 | 77.06642 | 4884.5 | LS 15 | WSW-ENE |
| 11 | 42 | 0.001376 | 32.97093 | 76.95813 | 4659.5 | LS 10 | ENE-WSW |
| 12 | 43 | 0.001609 | 32.97061 | 76.95857 | 4659.333333 | LS 11 | ENE-WSW |
| 38 | 73 | 0.001665 | 32.86476 | 77.47251 | 5263.666667 | LS 46 | SSW-NNE |
| 20 | 51 | 0.001817 | 32.65654 | 78.20357 | 5684.5 | LS 56 | E-W |
| 47 | 81 | 0.002059 | 32.61441 | 76.87291 | 2966 | LS 8 | SW-NE |
| 19 | 50 | 0.002329 | 32.61063 | 78.08077 | 5184.666667 | LS 54 | SE-NW |
| 31 | 66 | 0.003567 | 32.69591 | 77.36307 | 5060.8 | LS 29 | SE-NW |
| 6 | glacial lake4 | 0.004205 | 33.04329 | 76.78916 | 4011.8 | LS 2 | NW-SE |
| 63 | 97 | 0.004531 | 32.72744 | 77.5388 | 5237.333333 | LS 48 | W-E |
| 66 | 100 | 0.005317 | 32.76493 | 77.23075 | 4720.5 | LS 22 | SW-NE |
| 59 | 93 | 0.005646 | 32.74359 | 77.18915 | 5003.857143 | LS 18 | SSW-NNE |
| 45 | 79 | 0.006593 | 32.74771 | 77.10629 | 4511.666667 | LS 16 | SW-NE |
| 27 | 61 | 0.006707 | 32.75651 | 77.39387 | 4897 | LS 36 | ESE-WNW |
| 24 | 58 | 0.006983 | 32.5727 | 76.83775 | 3942 | LS 6 | SW-NE |
| 34 | 69 | 0.007035 | 32.68967 | 77.36037 | 5160.75 | LS 28 | S-N |
| 49 | 83 | 0.00734 | 32.75409 | 77.44164 | 5212.625 | LS 42 | NE-SW |
| 17 | 48 | 0.007669 | 32.85774 | 77.40918 | 5191.090909 | LS 40 | NNE-SSW |
| 1 | 56 | 0.00839 | 32.521 | 76.86944 | 5001.090909 | LS 7 | SW-NE |
| 2 | 57 | 0.009258 | 32.39355 | 77.30844 | 4530.818182 | LS 24 | SSE-NNW |
| 42 | 76 | 0.010045 | 32.8756 | 77.16344 | 5286.166667 | LS 17 | NNW-SSE |
| 15 | 46 | 0.010205 | 32.76463 | 77.32747 | 5232.230769 | LS 25 | NE-SW |
| 10 | 40 | 0.011138 | 32.98569 | 76.96765 | 5017.666667 | LS 12 | S-N |
| 0 | 110 | 0.011818 | 32.52523 | 77.94242 | 5281.3125 | LS 52 | NW-SE |
| 54 | 88 | 0.012354 | 32.09083 | 78.22806 | 4137.125 | LS 58 | NNW-SSE |
| 43 | 77 | 0.012605 | 32.9218 | 77.00982 | 5262.714286 | LS 13 | NNE-SSW |
| 33 | 68 | 0.013085 | 32.69337 | 77.36614 | 5096.933333 | LS 30 | SE-NW |
| 7 | glacial lake17 | 0.013478 | 33.0978 | 76.79209 | 5026.944444 | LS 3 | WNW-ESE |
| 41 | 75 | 0.013788 | 32.72274 | 77.37694 | 5299.176471 | LS 32 | W-E |
| 37 | 72 | 0.013924 | 32.83398 | 77.39424 | 5236.9 | LS 37 | WNW-ESE |
| 25 | 59 | 0.014765 | 32.92307 | 76.83278 | 4874.052632 | LS 5 | SSW-NNE |
| 40 | 74 | 0.014778 | 32.72386 | 77.3778 | 5284.45 | LS 33 | W-E |
| 9 | 31 | 0.016452 | 33.06591 | 76.82401 | 5022.526316 | LS 4 | WNW-ESE |
| 64 | 98 | 0.019666 | 32.38052 | 78.121 | 4962.565217 | LS 55 | SW-NE |
| 55 | 89 | 0.020721 | 32.41579 | 78.21988 | 5476 | LS 57 | WNW-ESE |
| 48 | 82 | 0.021354 | 32.71324 | 77.01694 | 4640.230769 | LS 14 | NE-SW |
| 36 | 71 | 0.022012 | 32.82713 | 77.38857 | 5298.851852 | LS 35 | SSW-NNE |
| 8 | glacial lake18 | 0.02226 | 33.10043 | 76.7853 | 5057.214286 | LS 1 | ESE-WNW |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 53 | 87 | 0.022673 | 32.2047 | 78.41806 | 5611.466667 | LS 62 | NE-SW |
| 14 | 45 | 0.022797 | 32.78638 | 77.21822 | 5112.733333 | LS 20 | E-W |
| 67 | 101 | 0.022887 | 32.61028 | 77.91205 | 5344.586207 | LS 51 | S-N |
| 44 | 78 | 0.02297 | 32.86671 | 76.93182 | 4995.724138 | LS 9 | ESE-WNW |
| 61 | 95 | 0.023498 | 32.79506 | 77.45799 | 4927 | LS 45 | S-N |
| 23 | 55 | 0.02352 | 32.24035 | 77.44922 | 4592.103448 | LS 44 | S-N |
| 56 | 90 | 0.025572 | 32.31471 | 78.3681 | 4817.235294 | LS 60 | SW-NE |
| 16 | 47 | 0.029096 | 32.85387 | 77.4001 | 5223.657143 | LS 39 | WSW-ENE |
| 26 | 60 | 0.037681 | 32.76274 | 77.39753 | 4761.978723 | LS 38 | E-W |
| 18 | 49 | 0.038833 | 32.60934 | 77.9533 | 4942.222222 | LS 53 | SSE-NNW |
| 13 | 44 | 0.042011 | 32.84452 | 77.28032 | 4875.836364 | LS 23 | SSE-NNW |
| 60 | 94 | 0.048875 | 32.70486 | 77.34777 | 4759.2 | LS 27 | SE-NW |
| 35 | 70 | 0.052743 | 32.76223 | 77.19531 | 4767.746032 | LS 19 | ESE-WNW |
| 22 | 54 | 0.052763 | 32.24535 | 77.44809 | 4483.876923 | LS 43 | SSE-NNW |
| 21 | 52 | 0.053316 | 32.14919 | 78.48776 | 5273.924242 | LS 63 | S-N |
| 52 | 86 | 0.057296 | 31.96489 | 78.41564 | 4875.959459 | LS 61 | SSW-NNE |
| 32 | 67 | 0.069579 | 32.69312 | 77.3724 | 5145.057471 | LS 31 | WNW-ESE |
| 39 | 64 | 0.080947 | 32.72282 | 77.32967 | 4553.83 | LS 26 | SE-NW |
| 29 | 63 | 0.101729 | 32.72194 | 77.41297 | 5127.062016 | LS 41 | N-S |
| 28 | 62 | 0.111307 | 32.72107 | 77.38444 | 5237.921429 | LS 34 | WSW-ENE |
| 65 | 99 | 0.14444 | 32.36277 | 78.27242 | 5364.472527 | LS 59 | S-N |
| 62 | 96 | 0.179346 | 32.79265 | 77.50341 | 5055.6 | LS 47 | WSW-ENE |
| 4 | Chandra Tal | 0.493572 | 32.48266 | 77.61468 | 4276.178689 | LS 50 | NNW-SSE |
| 3 | Sissu | 0.912417 | 32.52486 | 77.2193 | 4090.11535 | LS 21 | SSW-NNE |
| 5 | Samudri Tapu | 1.353594 | 32.49876 | 77.54654 | 4156.650179 | LS 49 | WNW-ESE |

| Code | Area (In $KM^2$) | Latitude | Longitude | Mean Altitude Above MSL (In Metres) | Orientation |
|---|---|---|---|---|---|
| LS 15 | 0.001069399 | 32.67181178 | 77.06642246 | 4884.5 | WSW-ENE |
| LS 10 | 0.00137576 | 32.97092544 | 76.95813283 | 4659.5 | ENE-WSW |
| LS 11 | 0.001609209 | 32.97060831 | 76.95857453 | 4659.333333 | ENE-WSW |
| LS 46 | 0.001665192 | 32.86476118 | 77.47250878 | 5263.666667 | SSW-NNE |
| LS 56 | 0.001816752 | 32.65654014 | 78.20357314 | 5684.5 | E-W |
| LS 8 | 0.00205899 | 32.61441025 | 76.87290889 | 2966 | SW-NE |
| LS 54 | 0.002328792 | 32.61062633 | 78.08076587 | 5184.666667 | SE-NW |
| LS 29 | 0.003567396 | 32.6959096 | 77.36306667 | 5060.8 | SE-NW |
| LS 2 | 0.004204571 | 33.04328804 | 76.7891605 | 4011.8 | NW-SE |
| LS 48 | 0.004531251 | 32.72744165 | 77.5387985 | 5237.333333 | W-E |
| LS 22 | 0.005316578 | 32.76492614 | 77.23075024 | 4720.5 | SW-NE |
| LS 18 | 0.005645915 | 32.74358864 | 77.18915147 | 5003.857143 | SSW-NNE |
| LS 16 | 0.006593425 | 32.74770716 | 77.10628795 | 4511.666667 | SW-NE |
| LS 36 | 0.006707396 | 32.75651298 | 77.3938693 | 4897 | ESE-WNW |
| LS 6 | 0.006982681 | 32.57270026 | 76.83775219 | 3942 | SW-NE |
| LS 28 | 0.007035125 | 32.68966604 | 77.36037265 | 5160.75 | S-N |
| LS 42 | 0.007340364 | 32.75408578 | 77.44164148 | 5212.625 | NE-SW |
| LS 40 | 0.007668689 | 32.85774346 | 77.40918391 | 5191.090909 | NNE-SSW |
| LS 7 | 0.008390301 | 32.52099558 | 76.86943907 | 5001.090909 | SW-NE |
| LS 24 | 0.009257745 | 32.39354578 | 77.30844289 | 4530.818182 | SSE-NNW |
| LS 17 | 0.010045154 | 32.87560008 | 77.16344001 | 5286.166667 | NNW-SSE |
| LS 25 | 0.010205122 | 32.76462746 | 77.32747026 | 5232.230769 | NE-SW |
| LS 12 | 0.011138186 | 32.98569126 | 76.96765013 | 5017.666667 | S-N |
| LS 52 | 0.011817862 | 32.52522505 | 77.94241831 | 5281.3125 | NW-SE |
| LS 58 | 0.012353621 | 32.09083271 | 78.2280576 | 4137.125 | NNW-SSE |
| LS 13 | 0.012605349 | 32.92180144 | 77.00982467 | 5262.714286 | NNE-SSW |
| LS 30 | 0.013084642 | 32.69337221 | 77.36614214 | 5096.933333 | SE-NW |
| LS 3 | 0.013478119 | 33.09779735 | 76.79209179 | 5026.944444 | WNW-ESE |
| LS 32 | 0.01378798 | 32.72273534 | 77.37693777 | 5299.176471 | W-E |
| LS 37 | 0.013924204 | 32.83397544 | 77.39423928 | 5236.9 | WNW-ESE |
| LS 5 | 0.014764806 | 32.92307293 | 76.83277657 | 4874.052632 | SSW-NNE |
| LS 33 | 0.014778291 | 32.72386309 | 77.37779551 | 5284.45 | W-E |
| LS 4 | 0.016452083 | 33.06591107 | 76.82400923 | 5022.526316 | WNW-ESE |
| LS 55 | 0.019665671 | 32.38051951 | 78.12100366 | 4962.565217 | SW-NE |
| LS 57 | 0.020721319 | 32.41578887 | 78.21988344 | 5476 | WNW-ESE |
| LS 14 | 0.021353667 | 32.71324216 | 77.01693976 | 4640.230769 | NE-SW |
| LS 35 | 0.022011528 | 32.82713213 | 77.38857451 | 5298.851852 | SSW-NNE |
| LS 1 | 0.022259628 | 33.10043161 | 76.78529605 | 5057.214286 | ESE-WNW |
| LS 62 | 0.022672873 | 32.20470124 | 78.41806164 | 5611.466667 | NE-SW |
| LS 20 | 0.02279658 | 32.78637795 | 77.21822369 | 5112.733333 | E-W |

| | | | | | |
|---|---|---|---|---|---|
| LS 51 | 0.022887027 | 32.61028122 | 77.91205049 | 5344.586207 | S-N |
| LS 9 | 0.022969877 | 32.8667121 | 76.93181558 | 4995.724138 | ESE-WNW |
| LS 45 | 0.023497709 | 32.79506324 | 77.45799216 | 4927 | S-N |
| LS 44 | 0.023519573 | 32.24035445 | 77.4492198 | 4592.103448 | S-N |
| LS 60 | 0.02557197 | 32.3147079 | 78.3681002 | 4817.235294 | SW-NE |
| LS 39 | 0.029095957 | 32.85386583 | 77.40009759 | 5223.657143 | WSW-ENE |
| LS 38 | 0.037680674 | 32.76274469 | 77.397529 | 4761.978723 | E-W |
| LS 53 | 0.038832958 | 32.60933942 | 77.95329851 | 4942.222222 | SSE-NNW |
| LS 23 | 0.042011426 | 32.84451987 | 77.28031727 | 4875.836364 | SSE-NNW |
| LS 27 | 0.048875063 | 32.70485969 | 77.34776972 | 4759.2 | SE-NW |
| LS 19 | 0.052742792 | 32.76222887 | 77.19530786 | 4767.746032 | ESE-WNW |
| LS 43 | 0.052763111 | 32.24535382 | 77.44808797 | 4483.876923 | SSE-NNW |
| LS 63 | 0.053315797 | 32.14919036 | 78.48776003 | 5273.924242 | S-N |
| LS 61 | 0.057295793 | 31.96488673 | 78.41564469 | 4875.959459 | SSW-NNE |
| LS 31 | 0.06957931 | 32.69311916 | 77.37240497 | 5145.057471 | WNW-ESE |
| LS 26 | 0.080946675 | 32.72281894 | 77.32967202 | 4553.83 | SE-NW |
| LS 41 | 0.10172889 | 32.72193838 | 77.41297484 | 5127.062016 | N-S |
| LS 34 | 0.111307061 | 32.72107234 | 77.38444422 | 5237.921429 | WSW-ENE |
| LS 59 | 0.144440361 | 32.36277463 | 78.27242125 | 5364.472527 | S-N |
| LS 47 | 0.179345781 | 32.79265151 | 77.50341174 | 5055.6 | WSW-ENE |
| LS 50 | 0.493571716 | 32.48266137 | 77.6146769 | 4276.178689 | NNW-SSE |
| LS 21 | 0.912416708 | 32.52486 | 77.21930161 | 4090.11535 | SSW-NNE |
| LS 49 | 1.353593785 | 32.49875778 | 77.54654285 | 4156.650179 | WNW-ESE |

| Code | Area (in $Km^2$) | Latitude | Longitude | Mean altitude above MSL (in metres) | Orientation |
|---|---|---|---|---|---|
| LS 8 | 0.00205899 | 32.61441025 | 76.87290889 | 2966 | SW-NE |
| LS 6 | 0.006982681 | 32.57270026 | 76.83775219 | 3942 | SW-NE |
| LS 2 | 0.004204571 | 33.04328804 | 76.7891605 | 4011.8 | NW-SE |
| LS 21 | 0.912416708 | 32.52486 | 77.21930161 | 4090.11535 | SSW-NNE |
| LS 58 | 0.012353621 | 32.09083271 | 78.2280576 | 4137.125 | NNW-SSE |
| LS 49 | 1.353593785 | 32.49875778 | 77.54654285 | 4156.650179 | WNW-ESE |
| LS 50 | 0.493571716 | 32.48266137 | 77.6146769 | 4276.178689 | NNW-SSE |
| LS 43 | 0.052763111 | 32.24535382 | 77.44808797 | 4483.876923 | SSE-NNW |
| LS 16 | 0.006593425 | 32.74770716 | 77.10628795 | 4511.666667 | SW-NE |
| LS 24 | 0.009257745 | 32.39354578 | 77.30844289 | 4530.818182 | SSE-NNW |
| LS 26 | 0.080946675 | 32.72281894 | 77.32967202 | 4553.83 | SE-NW |
| LS 44 | 0.023519573 | 32.24035445 | 77.4492198 | 4592.103448 | S-N |
| LS 14 | 0.021353667 | 32.71324216 | 77.01693976 | 4640.230769 | NE-SW |
| LS 11 | 0.001609209 | 32.97060831 | 76.95857453 | 4659.333333 | ENE-WSW |
| LS 10 | 0.00137576 | 32.97092544 | 76.95813283 | 4659.5 | ENE-WSW |
| LS 22 | 0.005316578 | 32.76492614 | 77.23075024 | 4720.5 | SW-NE |
| LS 27 | 0.048875063 | 32.70485969 | 77.34776972 | 4759.2 | SE-NW |
| LS 38 | 0.037680674 | 32.76274469 | 77.397529 | 4761.978723 | E-W |
| LS 19 | 0.052742792 | 32.76222887 | 77.19530786 | 4767.746032 | ESE-WNW |
| LS 60 | 0.02557197 | 32.3147079 | 78.3681002 | 4817.235294 | SW-NE |
| LS 5 | 0.014764806 | 32.92307293 | 76.83277657 | 4874.052632 | SSW-NNE |
| LS 23 | 0.042011426 | 32.84451987 | 77.28031727 | 4875.836364 | SSE-NNW |
| LS 61 | 0.057295793 | 31.96488673 | 78.41564469 | 4875.959459 | SSW-NNE |
| LS 15 | 0.001069399 | 32.67181178 | 77.06642246 | 4884.5 | WSW-ENE |
| LS 36 | 0.006707396 | 32.75651298 | 77.3938693 | 4897 | ESE-WNW |
| LS 45 | 0.023497709 | 32.79506324 | 77.45799216 | 4927 | S-N |
| LS 53 | 0.038832958 | 32.60933942 | 77.95329851 | 4942.222222 | SSE-NNW |
| LS 55 | 0.019665671 | 32.38051951 | 78.12100366 | 4962.565217 | SW-NE |
| LS 9 | 0.022969877 | 32.8667121 | 76.93181558 | 4995.724138 | ESE-WNW |
| LS 7 | 0.008390301 | 32.52099558 | 76.86943907 | 5001.090909 | SW-NE |
| LS 18 | 0.005645915 | 32.74358864 | 77.18915147 | 5003.857143 | SSW-NNE |
| LS 12 | 0.011138186 | 32.98569126 | 76.96765013 | 5017.666667 | S-N |
| LS 4 | 0.016452083 | 33.06591107 | 76.82400923 | 5022.526316 | WNW-ESE |
| LS 3 | 0.013478119 | 33.09779735 | 76.79209179 | 5026.944444 | WNW-ESE |
| LS 47 | 0.179345781 | 32.79265151 | 77.50341174 | 5055.6 | WSW-ENE |
| LS 1 | 0.022259628 | 33.10043161 | 76.78529605 | 5057.214286 | ESE-WNW |
| LS 29 | 0.003567396 | 32.6959096 | 77.36306667 | 5060.8 | SE-NW |
| LS 30 | 0.013084642 | 32.69337221 | 77.36614214 | 5096.933333 | SE-NW |
| LS 20 | 0.02279658 | 32.78637795 | 77.21822369 | 5112.733333 | E-W |
| LS 41 | 0.10172889 | 32.72193838 | 77.41297484 | 5127.062016 | N-S |

| | | | | | |
|---|---|---|---|---|---|
| LS 31 | 0.06957931 | 32.69311916 | 77.37240497 | 5145.057471 | WNW-ESE |
| LS 28 | 0.007035125 | 32.68966604 | 77.36037265 | 5160.75 | S-N |
| LS 54 | 0.002328792 | 32.61062633 | 78.08076587 | 5184.666667 | SE-NW |
| LS 40 | 0.007668689 | 32.85774346 | 77.40918391 | 5191.090909 | NNE-SSW |
| LS 42 | 0.007340364 | 32.75408578 | 77.44164148 | 5212.625 | NE-SW |
| LS 39 | 0.029095957 | 32.85386583 | 77.40009759 | 5223.657143 | WSW-ENE |
| LS 25 | 0.010205122 | 32.76462746 | 77.32747026 | 5232.230769 | NE-SW |
| LS 37 | 0.013924204 | 32.83397544 | 77.39423928 | 5236.9 | WNW-ESE |
| LS 48 | 0.004531251 | 32.72744165 | 77.5387985 | 5237.333333 | W-E |
| LS 34 | 0.111307061 | 32.72107234 | 77.38444422 | 5237.921429 | WSW-ENE |
| LS 13 | 0.012605349 | 32.92180144 | 77.00982467 | 5262.714286 | NNE-SSW |
| LS 46 | 0.001665192 | 32.86476118 | 77.47250878 | 5263.666667 | SSW-NNE |
| LS 63 | 0.053315797 | 32.14919036 | 78.48776003 | 5273.924242 | S-N |
| LS 52 | 0.011817862 | 32.52522505 | 77.94241831 | 5281.3125 | NW-SE |
| LS 33 | 0.014778291 | 32.72386309 | 77.37779551 | 5284.45 | W-E |
| LS 17 | 0.010045154 | 32.87560008 | 77.16344001 | 5286.166667 | NNW-SSE |
| LS 35 | 0.022011528 | 32.82713213 | 77.38857451 | 5298.851852 | SSW-NNE |
| LS 32 | 0.01378798 | 32.72273534 | 77.37693777 | 5299.176471 | W-E |
| LS 51 | 0.022887027 | 32.61028122 | 77.91205049 | 5344.586207 | S-N |
| LS 59 | 0.144440361 | 32.36277463 | 78.27242125 | 5364.472527 | S-N |
| LS 57 | 0.020721319 | 32.41578887 | 78.21988344 | 5476 | WNW-ESE |
| LS 62 | 0.022672873 | 32.20470124 | 78.41806164 | 5611.466667 | NE-SW |
| LS 56 | 0.001816752 | 32.65654014 | 78.20357314 | 5684.5 | E-W |

| Name | Area (in sq. km) | Latitude | Longitude | Mean altitude above MSL (in meters) | code | type |
|---|---|---|---|---|---|---|
| glacial lake18 | 0.02226 | 33.10043 | 76.7853 | 5057.214 | LS1 | supra-glacial |
| glacial lake4 | 0.004205 | 33.04329 | 76.78916 | 4011.8 | LS 2 | supra-glacial |
| glacial lake17 | 0.013478 | 33.0978 | 76.79209 | 5026.944 | LS 3 | morrain-dammed |
| 31 | 0.016452 | 33.06591 | 76.82401 | 5022.526 | LS 4 | morrain-dammed |
| 59 | 0.014765 | 32.92307 | 76.83278 | 4874.053 | LS 5 | morrain-dammed |
| 58 | 0.006983 | 32.5727 | 76.83775 | 3942 | LS 6 | pro-glacial |
| 56 | 0.00839 | 32.521 | 76.86944 | 5001.091 | LS 7 | morrain-dammed |
| 81 | 0.002059 | 32.61441 | 76.87291 | 2966 | LS 8 | blocked |
| 78 | 0.02297 | 32.86671 | 76.93182 | 4995.724 | LS 9 | blocked |
| 42 | 0.001376 | 32.97093 | 76.95813 | 4659.5 | LS 10 | supra-glacial |
| 43 | 0.001609 | 32.97061 | 76.95857 | 4659.333 | LS 11 | supra-glacial |
| 40 | 0.011138 | 32.98569 | 76.96765 | 5017.667 | LS 12 | supra-glacial |
| 77 | 0.012605 | 32.9218 | 77.00982 | 5262.714 | LS 13 | morrain-dammed |
| 82 | 0.021354 | 32.71324 | 77.01694 | 4640.231 | LS 14 | morrain-dammed |
| 80 | 0.001069 | 32.67181 | 77.06642 | 4884.5 | LS 15 | supra-glacial |
| 79 | 0.006593 | 32.74771 | 77.10629 | 4511.667 | LS 16 | supra-glacial |
| 76 | 0.010045 | 32.8756 | 77.16344 | 5286.167 | LS 17 | pro-glacial |
| 93 | 0.005646 | 32.74359 | 77.18915 | 5003.857 | LS 18 | supra-glacial |
| 70 | 0.052743 | 32.76223 | 77.19531 | 4767.746 | LS 19 | morrain-dammed |
| 45 | 0.022797 | 32.78638 | 77.21822 | 5112.733 | LS 20 | blocked |
| Sissupra-glacial | 0.912417 | 32.52486 | 77.2193 | 4090.115 | LS 21 | pro-glacial |
| 100 | 0.005317 | 32.76493 | 77.23075 | 4720.5 | LS 22 | pro-glacial |
| 44 | 0.042011 | 32.84452 | 77.28032 | 4875.836 | LS 23 | blocked |
| 57 | 0.009258 | 32.39355 | 77.30844 | 4530.818 | LS 24 | supra-glacial |
| 46 | 0.010205 | 32.76463 | 77.32747 | 5232.231 | LS 25 | blocked |
| 64 | 0.080947 | 32.72282 | 77.32967 | 4553.83 | LS 26 | morrain-dammed |
| 94 | 0.048875 | 32.70486 | 77.34777 | 4759.2 | LS 27 | pro-glacial |
| 69 | 0.007035 | 32.68967 | 77.36037 | 5160.75 | LS 28 | supra-glacial |
| 66 | 0.003567 | 32.69591 | 77.36307 | 5060.8 | LS 29 | morrain-dammed |
| 68 | 0.013085 | 32.69337 | 77.36614 | 5096.933 | LS 30 | morrain-dammed |
| 67 | 0.069579 | 32.69312 | 77.3724 | 5145.057 | LS 31 | morrain-dammed |
| 75 | 0.013788 | 32.72274 | 77.37694 | 5299.176 | LS 32 | blocked |
| 74 | 0.014778 | 32.72386 | 77.3778 | 5284.45 | LS 33 | blocked |
| 62 | 0.111307 | 32.72107 | 77.38444 | 5237.921 | LS 34 | pro-glacial |
| 71 | 0.022012 | 32.82713 | 77.38857 | 5298.852 | LS 35 | pro-glacial |
| 61 | 0.006707 | 32.75651 | 77.39387 | 4897 | LS 36 | blocked |
| 72 | 0.013924 | 32.83398 | 77.39424 | 5236.9 | LS 37 | morrain-dammed |
| 60 | 0.037681 | 32.76274 | 77.39753 | 4761.979 | LS 38 | blocked |
| 47 | 0.029096 | 32.85387 | 77.4001 | 5223.657 | LS 39 | pro-glacial |

| | | | | | | |
|---|---|---|---|---|---|---|
| 48 | 0.007669 | 32.85774 | 77.40918 | 5191.091 | LS 40 | pro-glacial |
| 63 | 0.101729 | 32.72194 | 77.41297 | 5127.062 | LS 41 | pro-glacial |
| 83 | 0.00734 | 32.75409 | 77.44164 | 5212.625 | LS 42 | pro-glacial |
| 54 | 0.052763 | 32.24535 | 77.44809 | 4483.877 | LS 43 | morrain-dammed |
| 55 | 0.02352 | 32.24035 | 77.44922 | 4592.103 | LS 44 | morrain-dammed |
| 95 | 0.023498 | 32.79506 | 77.45799 | 4927 | LS 45 | pro-glacial |
| 73 | 0.001665 | 32.86476 | 77.47251 | 5263.667 | LS 46 | morrain-dammed |
| 96 | 0.179346 | 32.79265 | 77.50341 | 5055.6 | LS 47 | blocked |
| 97 | 0.004531 | 32.72744 | 77.5388 | 5237.333 | LS 48 | morrain-dammed |
| Samudri Tapu | 1.353594 | 32.49876 | 77.54654 | 4156.65 | LS 49 | pro-glacial |
| Chandra Tal | 0.493572 | 32.48266 | 77.61468 | 4276.179 | LS 50 | valley |
| 101 | 0.022887 | 32.61028 | 77.91205 | 5344.586 | LS 51 | supra-glacial |
| 110 | 0.011818 | 32.52523 | 77.94242 | 5281.313 | LS 52 | pro-glacial |
| 49 | 0.038833 | 32.60934 | 77.9533 | 4942.222 | LS 53 | valley |
| 50 | 0.002329 | 32.61063 | 78.08077 | 5184.667 | LS 54 | pro-glacial |
| 98 | 0.019666 | 32.38052 | 78.121 | 4962.565 | LS 55 | pro-glacial |
| 51 | 0.001817 | 32.65654 | 78.20357 | 5684.5 | LS 56 | supra-glacial |
| 89 | 0.020721 | 32.41579 | 78.21988 | 5476 | LS 57 | morrain-dammed |
| 88 | 0.012354 | 32.09083 | 78.22806 | 4137.125 | LS 58 | blocked |
| 99 | 0.14444 | 32.36277 | 78.27242 | 5364.473 | LS 59 | supra-glacial |
| 90 | 0.025572 | 32.31471 | 78.3681 | 4817.235 | LS 60 | blocked |
| 86 | 0.057296 | 31.96489 | 78.41564 | 4875.959 | LS 61 | supra-glacial |
| 87 | 0.022673 | 32.2047 | 78.41806 | 5611.467 | LS 62 | supra-glacial |
| 52 | 0.053316 | 32.14919 | 78.48776 | 5273.924 | LS 63 | supra-glacial |

| Code | Area (in $Km^2$) | Latitude | Longitude | Mean altitude above MSL (in metres) | Orientation |
|---|---|---|---|---|---|
| LS 25 | 0.010205 | 32.76463 | 77.32747026 | 5232.230769 | NE-SW |
| LS 10 | 0.001376 | 32.97093 | 76.95813283 | 4659.5 | ENE-WSW |
| LS 11 | 0.001609 | 32.97061 | 76.95857453 | 4659.333333 | ENE-WSW |
| LS 1 | 0.02226 | 33.10043 | 76.78529605 | 5057.214286 | ESE-WNW |
| LS 9 | 0.02297 | 32.86671 | 76.93181558 | 4995.724138 | ESE-WNW |
| LS 19 | 0.052743 | 32.76223 | 77.19530786 | 4767.746032 | ESE-WNW |
| LS 36 | 0.006707 | 32.75651 | 77.3938693 | 4897 | ESE-WNW |
| LS 20 | 0.022797 | 32.78638 | 77.21822369 | 5112.733333 | E-W |
| LS 38 | 0.037681 | 32.76274 | 77.397529 | 4761.978723 | E-W |
| LS 56 | 0.001817 | 32.65654 | 78.20357314 | 5684.5 | E-W |
| LS 14 | 0.021354 | 32.71324 | 77.01693976 | 4640.230769 | NE-SW |
| LS 42 | 0.00734 | 32.75409 | 77.44164148 | 5212.625 | NE-SW |
| LS 62 | 0.022673 | 32.2047 | 78.41806164 | 5611.466667 | NE-SW |
| LS 13 | 0.012605 | 32.9218 | 77.00982467 | 5262.714286 | NNE-SSW |
| LS 40 | 0.007669 | 32.85774 | 77.40918391 | 5191.090909 | NNE-SSW |
| LS 17 | 0.010045 | 32.8756 | 77.16344001 | 5286.166667 | NNW-SSE |
| LS 50 | 0.493572 | 32.48266 | 77.6146769 | 4276.178689 | NNW-SSE |
| LS 58 | 0.012354 | 32.09083 | 78.2280576 | 4137.125 | NNW-SSE |
| LS 41 | 0.101729 | 32.72194 | 77.41297484 | 5127.062016 | N-S |
| LS 2 | 0.004205 | 33.04329 | 76.7891605 | 4011.8 | NW-SE |
| LS 52 | 0.011818 | 32.52523 | 77.94241831 | 5281.3125 | NW-SE |
| LS 26 | 0.080947 | 32.72282 | 77.32967202 | 4553.83 | SE-NW |
| LS 27 | 0.048875 | 32.70486 | 77.34776972 | 4759.2 | SE-NW |
| LS 29 | 0.003567 | 32.69591 | 77.36306667 | 5060.8 | SE-NW |
| LS 30 | 0.013085 | 32.69337 | 77.36614214 | 5096.933333 | SE-NW |
| LS 54 | 0.002329 | 32.61063 | 78.08076587 | 5184.666667 | SE-NW |
| LS 12 | 0.011138 | 32.98569 | 76.96765013 | 5017.666667 | S-N |
| LS 28 | 0.007035 | 32.68967 | 77.36037265 | 5160.75 | S-N |
| LS 44 | 0.02352 | 32.24035 | 77.4492198 | 4592.103448 | S-N |
| LS 45 | 0.023498 | 32.79506 | 77.45799216 | 4927 | S-N |
| LS 51 | 0.022887 | 32.61028 | 77.91205049 | 5344.586207 | S-N |
| LS 59 | 0.14444 | 32.36277 | 78.27242125 | 5364.472527 | S-N |
| LS 63 | 0.053316 | 32.14919 | 78.48776003 | 5273.924242 | S-N |
| LS 23 | 0.042011 | 32.84452 | 77.28031727 | 4875.836364 | SSE-NNW |
| LS 24 | 0.009258 | 32.39355 | 77.30844289 | 4530.818182 | SSE-NNW |
| LS 43 | 0.052763 | 32.24535 | 77.44808797 | 4483.876923 | SSE-NNW |
| LS 53 | 0.038833 | 32.60934 | 77.95329851 | 4942.222222 | SSE-NNW |
| LS 5 | 0.014765 | 32.92307 | 76.83277657 | 4874.052632 | SSW-NNE |
| LS 18 | 0.005646 | 32.74359 | 77.18915147 | 5003.857143 | SSW-NNE |
| LS 21 | 0.912417 | 32.52486 | 77.21930161 | 4090.11535 | SSW-NNE |

| | | | | | |
|---|---|---|---|---|---|
| LS 35 | 0.022012 | 32.82713 | 77.38857451 | 5298.851852 | SSW-NNE |
| LS 46 | 0.001665 | 32.86476 | 77.47250878 | 5263.666667 | SSW-NNE |
| LS 61 | 0.057296 | 31.96489 | 78.41564469 | 4875.959459 | SSW-NNE |
| LS 6 | 0.006983 | 32.5727 | 76.83775219 | 3942 | SW-NE |
| LS 7 | 0.00839 | 32.521 | 76.86943907 | 5001.090909 | SW-NE |
| LS 8 | 0.002059 | 32.61441 | 76.87290889 | 2966 | SW-NE |
| LS 16 | 0.006593 | 32.74771 | 77.10628795 | 4511.666667 | SW-NE |
| LS 22 | 0.005317 | 32.76493 | 77.23075024 | 4720.5 | SW-NE |
| LS 55 | 0.019666 | 32.38052 | 78.12100366 | 4962.565217 | SW-NE |
| LS 60 | 0.025572 | 32.31471 | 78.3681002 | 4817.235294 | SW-NE |
| LS 32 | 0.013788 | 32.72274 | 77.37693777 | 5299.176471 | W-E |
| LS 33 | 0.014778 | 32.72386 | 77.37779551 | 5284.45 | W-E |
| LS 48 | 0.004531 | 32.72744 | 77.5387985 | 5237.333333 | W-E |
| LS 3 | 0.013478 | 33.0978 | 76.79209179 | 5026.944444 | WNW-ESE |
| LS 4 | 0.016452 | 33.06591 | 76.82400923 | 5022.526316 | WNW-ESE |
| LS 31 | 0.069579 | 32.69312 | 77.37240497 | 5145.057471 | WNW-ESE |
| LS 37 | 0.013924 | 32.83398 | 77.39423928 | 5236.9 | WNW-ESE |
| LS 49 | 1.353594 | 32.49876 | 77.54654285 | 4156.650179 | WNW-ESE |
| LS 57 | 0.020721 | 32.41579 | 78.21988344 | 5476 | WNW-ESE |
| LS 15 | 0.001069 | 32.67181 | 77.06642246 | 4884.5 | WSW-ENE |
| LS 34 | 0.111307 | 32.72107 | 77.38444422 | 5237.921429 | WSW-ENE |
| LS 39 | 0.029096 | 32.85387 | 77.40009759 | 5223.657143 | WSW-ENE |
| LS 47 | 0.179346 | 32.79265 | 77.50341174 | 5055.6 | WSW-ENE |

| Code | Area (in $Km^2$) | Latitude | Longitude | Mean altitude above MSL (in metres) | Orientation |
|---|---|---|---|---|---|
| LS 1 | 0.022259628 | 33.10043161 | 76.78529605 | 5057.214286 | ESE-WNW |
| LS 2 | 0.004204571 | 33.04328804 | 76.7891605 | 4011.8 | NW-SE |
| LS 3 | 0.013478119 | 33.09779735 | 76.79209179 | 5026.944444 | WNW-ESE |
| LS 4 | 0.016452083 | 33.06591107 | 76.82400923 | 5022.526316 | WNW-ESE |
| LS 5 | 0.014764806 | 32.92307293 | 76.83277657 | 4874.052632 | SSW-NNE |
| LS 6 | 0.006982681 | 32.57270026 | 76.83775219 | 3942 | SW-NE |
| LS 7 | 0.008390301 | 32.52099558 | 76.86943907 | 5001.090909 | SW-NE |
| LS 8 | 0.00205899 | 32.61441025 | 76.87290889 | 2966 | SW-NE |
| LS 9 | 0.022969877 | 32.8667121 | 76.93181558 | 4995.724138 | ESE-WNW |
| LS 10 | 0.00137576 | 32.97092544 | 76.95813283 | 4659.5 | ENE-WSW |
| LS 11 | 0.001609209 | 32.97060831 | 76.95857453 | 4659.333333 | ENE-WSW |
| LS 12 | 0.011138186 | 32.98569126 | 76.96765013 | 5017.666667 | S-N |
| LS 13 | 0.012605349 | 32.92180144 | 77.00982467 | 5262.714286 | NNE-SSW |
| LS 14 | 0.021353667 | 32.71324216 | 77.01693976 | 4640.230769 | NE-SW |
| LS 15 | 0.001069399 | 32.67181178 | 77.06642246 | 4884.5 | WSW-ENE |
| LS 16 | 0.006593425 | 32.74770716 | 77.10628795 | 4511.666667 | SW-NE |
| LS 17 | 0.010045154 | 32.87560008 | 77.16344001 | 5286.166667 | NNW-SSE |
| LS 18 | 0.005645915 | 32.74358864 | 77.18915147 | 5003.857143 | SSW-NNE |
| LS 19 | 0.052742792 | 32.76222887 | 77.19530786 | 4767.746032 | ESE-WNW |
| LS 20 | 0.02279658 | 32.78637795 | 77.21822369 | 5112.733333 | E-W |
| LS 21 | 0.912416708 | 32.52486 | 77.21930161 | 4090.11535 | SSW-NNE |
| LS 22 | 0.005316578 | 32.76492614 | 77.23075024 | 4720.5 | SW-NE |
| LS 23 | 0.042011426 | 32.84451987 | 77.28031727 | 4875.836364 | SSE-NNW |
| LS 24 | 0.009257745 | 32.39354578 | 77.30844289 | 4530.818182 | SSE-NNW |
| LS 25 | 0.010205122 | 32.76462746 | 77.32747026 | 5232.230769 | NE-SW |
| LS 26 | 0.080946675 | 32.72281894 | 77.32967202 | 4553.83 | SE-NW |
| LS 27 | 0.048875063 | 32.70485969 | 77.34776972 | 4759.2 | SE-NW |
| LS 28 | 0.007035125 | 32.68966604 | 77.36037265 | 5160.75 | S-N |
| LS 29 | 0.003567396 | 32.6959096 | 77.36306667 | 5060.8 | SE-NW |
| LS 30 | 0.013084642 | 32.69337221 | 77.36614214 | 5096.933333 | SE-NW |
| LS 31 | 0.06957931 | 32.69311916 | 77.37240497 | 5145.057471 | WNW-ESE |
| LS 32 | 0.01378798 | 32.72273534 | 77.37693777 | 5299.176471 | W-E |
| LS 33 | 0.014778291 | 32.72386309 | 77.37779551 | 5284.45 | W-E |
| LS 34 | 0.111307061 | 32.72107234 | 77.38444422 | 5237.921429 | WSW-ENE |
| LS 35 | 0.022011528 | 32.82713213 | 77.38857451 | 5298.851852 | SSW-NNE |
| LS 36 | 0.006707396 | 32.75651298 | 77.3938693 | 4897 | ESE-WNW |
| LS 37 | 0.013924204 | 32.83397544 | 77.39423928 | 5236.9 | WNW-ESE |
| LS 38 | 0.037680674 | 32.76274469 | 77.397529 | 4761.978723 | E-W |
| LS 39 | 0.029095957 | 32.85386583 | 77.40009759 | 5223.657143 | WSW-ENE |

| | | | | | |
|---|---|---|---|---|---|
| LS 40 | 0.007668689 | 32.85774346 | 77.40918391 | 5191.090909 | NNE-SSW |
| LS 41 | 0.10172889 | 32.72193838 | 77.41297484 | 5127.062016 | N-S |
| LS 42 | 0.007340364 | 32.75408578 | 77.44164148 | 5212.625 | NE-SW |
| LS 43 | 0.052763111 | 32.24535382 | 77.44808797 | 4483.876923 | SSE-NNW |
| LS 44 | 0.023519573 | 32.24035445 | 77.4492198 | 4592.103448 | S-N |
| LS 45 | 0.023497709 | 32.79506324 | 77.45799216 | 4927 | S-N |
| LS 46 | 0.001665192 | 32.86476118 | 77.47250878 | 5263.666667 | SSW-NNE |
| LS 47 | 0.179345781 | 32.79265151 | 77.50341174 | 5055.6 | WSW-ENE |
| LS 48 | 0.004531251 | 32.72744165 | 77.5387985 | 5237.333333 | W-E |
| LS 49 | 1.353593785 | 32.49875778 | 77.54654285 | 4156.650179 | WNW-ESE |
| LS 50 | 0.493571716 | 32.48266137 | 77.6146769 | 4276.178689 | NNW-SSE |
| LS 51 | 0.022887027 | 32.61028122 | 77.91205049 | 5344.586207 | S-N |
| LS 52 | 0.011817862 | 32.52522505 | 77.94241831 | 5281.3125 | NW-SE |
| LS 53 | 0.038832958 | 32.60933942 | 77.95329851 | 4942.222222 | SSE-NNW |
| LS 54 | 0.002328792 | 32.61062633 | 78.08076587 | 5184.666667 | SE-NW |
| LS 55 | 0.019665671 | 32.38051951 | 78.12100366 | 4962.565217 | SW-NE |
| LS 56 | 0.001816752 | 32.65654014 | 78.20357314 | 5684.5 | E-W |
| LS 57 | 0.020721319 | 32.41578887 | 78.21988344 | 5476 | WNW-ESE |
| LS 58 | 0.012353621 | 32.09083271 | 78.2280576 | 4137.125 | NNW-SSE |
| LS 59 | 0.144440361 | 32.36277463 | 78.27242125 | 5364.472527 | S-N |
| LS 60 | 0.02557197 | 32.3147079 | 78.3681002 | 4817.235294 | SW-NE |
| LS 61 | 0.057295793 | 31.96488673 | 78.41564469 | 4875.959459 | SSW-NNE |
| LS 62 | 0.022672873 | 32.20470124 | 78.41806164 | 5611.466667 | NE-SW |
| LS 63 | 0.053315797 | 32.14919036 | 78.48776003 | 5273.924242 | S-N |
| Mean | 0.069731305 | | | 4915.058696 | |
| Range | | | | | |
| Min | 0.001069399 | | | 2966 | |
| Max | 1.353593785 | | | 5684.5 | |
| Sum | 4.39307223 | | | | |

| Code | Area (in $Km^2$) | Latitude | Longitude | Mean altitude above MSL (in Metres) | Orientation | Type | Volume 1 (cubic m) huggel |
|---|---|---|---|---|---|---|---|
| LS 1 | 0.022259628 | 33.10043161 | 76.78529605 | 5057.214286 | ESE-WNW | supra-glacial | 155063.21 |
| LS 2 | 0.004204571 | 33.04328804 | 76.7891605 | 4011.8 | NW-SE | supra-glacial | 14545.15 |
| LS 3 | 0.013478119 | 33.09779735 | 76.79209179 | 5026.944444 | WNW-ESE | morrain-dammed | 76051.35 |
| LS 4 | 0.016452083 | 33.06591107 | 76.82400923 | 5022.526316 | WNW-ESE | morrain-dammed | 100940.86 |
| LS 5 | 0.014764806 | 32.92307293 | 76.83277657 | 4874.052632 | SSW-NNE | morrain-dammed | 86563.88 |
| LS 6 | 0.006982681 | 32.57270026 | 76.83775219 | 3942 | SW-NE | pro-glacial | 29891.30 |
| LS 7 | 0.008390301 | 32.52099558 | 76.86943907 | 5001.090909 | SW-NE | morrain-dammed | 38796.94 |
| LS 8 | 0.00205899 | 32.61441025 | 76.87290889 | 2966 | SW-NE | blocked | 5277.43 |
| LS 9 | 0.022969877 | 32.8667121 | 76.93181558 | 4995.724138 | ESE-WNW | blocked | 162135.70 |
| LS 10 | 0.00137576 | 32.97092544 | 76.95813283 | 4659.5 | ENE-WSW | supra-glacial | 2976.90 |
| LS 11 | 0.001609209 | 32.97060831 | 76.95857453 | 4659.333333 | ENE-WSW | supra-glacial | 3718.97 |
| LS 12 | 0.011138186 | 32.98569126 | 76.96765013 | 5017.666667 | S-N | supra-glacial | 58010.94 |
| LS 13 | 0.012605349 | 32.92180144 | 77.00982467 | 5262.714286 | NNE-SSW | morrain-dammed | 69154.63 |
| LS 14 | 0.021353667 | 32.71324216 | 77.01693976 | 4640.230769 | NE-SW | morrain-dammed | 146178.75 |
| LS 15 | 0.001069399 | 32.67181178 | 77.06642246 | 4884.5 | WSW-ENE | supra-glacial | 2081.67 |
| LS 16 | 0.006593425 | 32.74770716 | 77.10628795 | 4511.666667 | SW-NE | supra-glacial | 27553.14 |
| LS 17 | 0.010045154 | 32.87560008 | 77.16344001 | 5286.166667 | NNW-SSE | pro-glacial | 50097.00 |
| LS 18 | 0.005645915 | 32.74358864 | 77.18915147 | 5003.857143 | SSW-NNE | supra-glacial | 22105.28 |
| LS 19 | 0.052742792 | 32.76222887 | 77.19530786 | 4767.746032 | ESE-WNW | morrain-dammed | 527843.24 |
| LS 20 | 0.02279658 | 32.78637795 | 77.21822369 | 5112.733333 | E-W | blocked | 160401.46 |
| LS 21 | 0.912416708 | 32.52486 | 77.21930161 | 4090.11535 | SSW-NNE | pro-glacial | 30234843.50 |
| LS 22 | 0.005316578 | 32.76492614 | 77.23075024 | 4720.5 | SW-NE | pro-glacial | 20296.96 |
| LS 23 | 0.042011426 | 32.84451987 | 77.28031727 | 4875.836364 | SSE-NNW | blocked | 382133.47 |
| LS 24 | 0.009257745 | 32.39354578 | 77.30844289 | 4530.818182 | SSE-NNW | supra-glacial | 44613.96 |
| LS 25 | 0.010205122 | 32.76462746 | 77.32747026 | 5232.230769 | NE-SW | blocked | 51233.64 |
| LS 26 | 0.080946675 | 32.72281894 | 77.32967202 | 4553.83 | SE-NW | morrain-dammed | 969786.07 |
| LS 27 | 0.048875063 | 32.70485969 | 77.34776972 | 4759.2 | SE-NW | pro-glacial | 473737.05 |
| LS 28 | 0.007035125 | 32.68966604 | 77.36037265 | 5160.75 | S-N | supra-glacial | 30210.60 |
| LS 29 | 0.003567396 | 32.6959096 | 77.36306667 | 5060.8 | SE-NW | morrain-dammed | 11517.87 |
| LS 30 | 0.013084642 | 32.69337221 | 77.36614214 | 5096.933333 | SE-NW | morrain-dammed | 72918.07 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| LS 31 | 0.06957931 | 32.69311916 | 77.37240497 | 5145.057471 | WNW-ESE | morrain-dammed | 782267.17 |
| LS 32 | 0.01378798 | 32.72273534 | 77.37693777 | 5299.176471 | W-E | blocked | 78546.03 |
| LS 33 | 0.014778291 | 32.72386309 | 77.37779551 | 5284.45 | W-E | blocked | 86676.17 |
| LS 34 | 0.111307061 | 32.72107234 | 77.38444422 | 5237.921429 | WSW-ENE | pro-glacial | 1524388.26 |
| LS 35 | 0.022011528 | 32.82713213 | 77.38857451 | 5298.851852 | SSW-NNE | pro-glacial | 152614.79 |
| LS 36 | 0.006707396 | 32.75651298 | 77.3938693 | 4897 | ESE-WNW | blocked | 28231.89 |
| LS 37 | 0.013924204 | 32.83397544 | 77.39423928 | 5236.9 | WNW-ESE | morrain-dammed | 79650.27 |
| LS 38 | 0.037680674 | 32.76274469 | 77.397529 | 4761.978723 | E-W | blocked | 327432.54 |
| LS 39 | 0.029095957 | 32.85386583 | 77.40009759 | 5223.657143 | WSW-ENE | pro-glacial | 226817.05 |
| LS 40 | 0.007668689 | 32.85774346 | 77.40918391 | 5191.090909 | NNE-SSW | pro-glacial | 34145.80 |
| LS 41 | 0.10172889 | 32.72193838 | 77.41297484 | 5127.062016 | N-S | pro-glacial | 1341541.94 |
| LS 42 | 0.007340364 | 32.75408578 | 77.44164148 | 5212.625 | NE-SW | pro-glacial | 32088.72 |
| LS 43 | 0.052763111 | 32.24535382 | 77.44808797 | 4483.876923 | SSE-NNW | morrain-dammed | 528132.02 |
| LS 44 | 0.023519573 | 32.24035445 | 77.4492198 | 4592.103448 | S-N | morrain-dammed | 167673.00 |
| LS 45 | 0.023497709 | 32.79506324 | 77.45799216 | 4927 | S-N | pro-glacial | 167451.71 |
| LS 46 | 0.001665192 | 32.86476118 | 77.47250878 | 5263.666667 | SSW-NNE | morrain-dammed | 3904.03 |
| LS 47 | 0.179345781 | 32.79265151 | 77.50341174 | 5055.6 | WSW-ENE | blocked | 3001060.79 |
| LS 48 | 0.004531251 | 32.72744165 | 77.5387985 | 5237.333333 | W-E | morrain-dammed | 16175.70 |
| LS 49 | 1.353593785 | 32.49875778 | 77.54654285 | 4156.650179 | WNW-ESE | pro-glacial | 52935473.07 |
| LS 50 | 0.493571716 | 32.48266137 | 77.6146769 | 4276.178689 | NNW-SSE | valley | 12635450.04 |
| LS 51 | 0.022887027 | 32.61028122 | 77.91205049 | 5344.586207 | S-N | supra-glacial | 161305.90 |
| LS 52 | 0.011817862 | 32.52522505 | 77.94241831 | 5281.3125 | NW-SE | pro-glacial | 63101.34 |
| LS 53 | 0.038832958 | 32.60933942 | 77.95329851 | 4942.222222 | SSE-NNW | valley | 341741.73 |
| LS 54 | 0.002328792 | 32.61062633 | 78.08076587 | 5184.666667 | SE-NW | pro-glacial | 6285.78 |
| LS 55 | 0.019665671 | 32.38051951 | 78.12100366 | 4962.565217 | SW-NE | pro-glacial | 130046.84 |
| LS 56 | 0.001816752 | 32.65654014 | 78.20357314 | 5684.5 | E-W | supra-glacial | 4418.08 |
| LS 57 | 0.020721319 | 32.41578887 | 78.21988344 | 5476 | WNW-ESE | morrain-dammed | 140070.29 |
| LS 58 | 0.012353621 | 32.09083271 | 78.2280576 | 4137.125 | NNW-SSE | blocked | 67201.85 |
| LS 59 | 0.144440361 | 32.36277463 | 78.27242125 | 5364.472527 | S-N | supra-glacial | 2206942.93 |
| LS 60 | 0.02557197 | 32.3147079 | 78.3681002 | 4817.235294 | SW-NE | blocked | 188824.56 |
| LS 61 | 0.057295793 | 31.96488673 | 78.41564469 | 4875.959459 | SSW-NNE | supra-glacial | 593700.78 |
| LS 62 | 0.022672873 | 32.20470124 | 78.41806164 | 5611.466667 | NE-SW | supra-glacial | 159166.86 |
| LS 63 | 0.053315797 | 32.14919036 | 78.48776003 | 5273.924242 | S-N | supra-glacial | 536004.86 |
| Mean | 0.069731305 | | | 4915.058696 | | | 784694.86 |
| Range | | | | | | | 0.00 |
| Min | 0.001069399 | | | 2966 | | | 2081.67 |
| Max | 1.353593785 | | | 5684.5 | | | 52935473.07 |
| Sum | 4.39307223 | | | | | | 281685432.39 |

**CALCULATED VELOCITY DATA FOR SAMUDRA TAPU LAKE**

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RiverCode,ReachCode,ProfileM,AlongF,Velocity,Profile,XSOID,OBJECTID
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tapunala,tandi,19000.000000000000000,0.254820000000000,6.135000000000000,P001,4,5
tapunala,tandi,19000.000000000000000,0.427950000000000,7.047000000000000,P001,4,6
tapunala,tandi,17708.540000000001000,0.263740000000000,3.428000000000000,P001,5,7
tapunala,tandi,17708.540000000001000,0.265270000000000,3.428000000000000,P001,5,8
tapunala,tandi,17708.540000000001000,0.436430000000000,7.029000000000000,P001,5,9
tapunala,tandi,17076.770000000000000,0.332240000000000,4.865000000000000,P001,6,10
tapunala,tandi,17076.770000000000000,0.338740000000000,4.865000000000000,P001,6,11
tapunala,tandi,17076.770000000000000,0.548540000000000,6.097000000000000,P001,6,12
tapunala,tandi,16000.000000000000000,0.414980000000000,4.996000000000000,P001,7,13
tapunala,tandi,16000.000000000000000,0.429630000000000,4.996000000000000,P001,7,14
tapunala,tandi,16000.000000000000000,0.538290000000000,6.474000000000000,P001,7,15
tapunala,tandi,15000.000000000000000,0.432860000000000,6.766000000000000,P001,8,16
tapunala,tandi,14001.910000000000000,0.420640000000000,6.839000000000000,P001,9,17
tapunala,tandi,13000.000000000000000,0.461670000000000,3.696000000000000,P001,10,18
tapunala,tandi,13000.000000000000000,0.465970000000000,3.696000000000000,P001,10,19
tapunala,tandi,13000.000000000000000,0.536080000000000,7.264000000000000,P001,10,20
tapunala,tandi,11980.549999999999000,0.280380000000000,2.262000000000000,P001,11,21
tapunala,tandi,11980.549999999999000,0.312490000000000,2.262000000000000,P001,11,22
tapunala,tandi,11980.549999999999000,0.411450000000000,7.448000000000000,P001,11,23
tapunala,tandi,11477.510000000000000,0.413320000000000,11.850000000000000,P001,12,24
tapunala,tandi,11000.000000000000000,0.519350000000000,4.562000000000000,P001,13,25
tapunala,tandi,10471.650000000000000,0.604510000000000,7.128000000000000,P001,14,26
tapunala,tandi,10000.000000000000000,0.559450000000000,11.368000000000000,P001,15,27
tapunala,tandi,9330.527000000000000,0.482550000000000,7.822000000000000,P001,16,28
tapunala,tandi,9000.000000000000000,0.521400000000000,8.186999999999999,P001,17,29
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tapunala,tandi,8000.000000000000000,0.566030000000000,3.038000000000000,P001,19,33
tapunala,tandi,7000.000000000000000,0.497490000000000,10.585000000000001,P001,20,34
tapunala,tandi,6000.000000000000000,0.506740000000000,7.172000000000000,P001,21,35
tapunala,tandi,5000.000000000000000,0.521740000000000,7.551000000000000,P001,22,36
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tapunala,tandi,4000.000000000000000,0.442920000000000,0.765000000000000,P001,23,40
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tapunala,tandi,4000.000000000000000,0.552390000000000,1.661000000000000,P001,23,43
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## CALCULATED MANNINGS COEFFICIENT DATA FOR SAMUDRA TAPU LAKE

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tapunala,tandi,15000.000000000000000,0.224150000000000,0.712120000000000,,N,,2000.000053503004400,4066.882000000000100
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