Preparation of
Hazard, Vulnerability & Risk Analysis atlas and report for the state of Himachal Pradesh

GLOF Hazard Risk Assessment

Composite Final Draft Report

(T6)

Prepared for

Disaster Management Cell, Department of Revenue

Government of Himachal Pradesh, Shimla

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VOLUME GUIDE

This series of reports present detailed technical and methodological documentation of the study entitled “Preparation of Hazard, Vulnerability & Risk Analysis Atlas and Report for the State of Himachal Pradesh” for DM Cell, Revenue Department, Himachal Pradesh.

Volume 1

Hazard Risk

This volume contains Technical papers on hazard risk assessment due to natural and man-made hazards within Himachal Pradesh as presented below.

1. Avalanche Hazard Risk
2. Climate Change & Flood Hazard Risk
3. Drought Hazard Risk
4. Earthquake Hazard Risk
5. Environmental & Industrial Hazard Risk
6. Forest Fire Hazard Risk
7. **GLOF Hazard Risk**
8. Landslide Hazard Risk

Volume 2

Vulnerability and Risk

This volume contains Technical papers on the Vulnerability and Risks to key elements at risk within Himachal Pradesh as presented below.

1. Socio-Economic Vulnerability and Risk
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Volume

1

Hazard Risk

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Abbreviations

ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
CSE	Centre for Science and Environment
DEM	Digital Elevation Model
ETM	Enhanced Thematic Mapper
GE	Google Earth
GHE	Green House Effect
GHG	Green House Gas
GIS	Geographical Information Systems
GSI	Geological Survey of India
HKH	Hindu Kush Himalaya
ICIMOD	International Centre for Integrated Mountain Development
IPCC	Intergovernmental Panel on Climate Change
QGis	Quantam Geographical Information System
SAR	Synthetic Aperture Radar
SRTM	Shuttle Radar Topography Mission
UNEO	United Nations Environmental Organization
WECS	Water and Energy Commission Secretariat
WMS	Web Map Service
WRS	Worldwide Reference System
WWF	World Wildlife Fund

Executive Summary

Glaciers along with other environmental systems act as moderators of climate system. Himachal Pradesh is donned with 1,239 glaciers of varying types and dimension, covering an area of approximately 2,473 km^2 which accounts to 4.44% of the state of Himachal Pradesh. These glaciers provide year-round supply of freshwater for domestic consumption and irrigation (most of the perennial springs are dependent on the glaciers for recharge) and also cater to electricity generation by supporting hydropower projects.

Glacier dynamics are closely related to glacial lake formation. The glacial lakes tend to breach when their respective blockades attain their resistivity threshold. Such breaches can occur in either when glaciers wane or wax. This results in glacial lake outburst which further lead to flash floods (in case of large glaciers) downstream, popularly known as glacial lake outburst floods (GLOFs). In some cases these floods are sudden when the melting is rapid, causing lake waters to swell and increase the pressure on retaining material, be it the end moraine or ablation valley.

The state of Himachal Pradesh has undergone significant infrastructural development over the past few decades. These developments are evident across the state including the northern regions of higher altitude. In order to assess the hazard risk due to GLOF, within this study a total of 1,239 glaciers were mapped and analyzed. Field survey information was used to validate select glaciers. Based on the possible risk potential and impact potential to the population, 11 Glacier lakes were selected for detailed analysis. The results from our analysis indicate that these select glacial lakes which are in Satluj, Chenab and Ravi basins are at risk and may breach.

Due to the nature of the risk and potential impact it may cause to people and infrastructure along their downstream we recommend incessant monitoring of these glaciers.

Chapter 1: Glacier Characteristics in Himachal Pradesh

1.1 Introduction

Glaciers form the largest mass of water resource contributing to around 76.66% of fresh water on Earth's surface. Glacier is a natural body of ice, originating on land with a distinctive movement that transports ice and debris from its area of accumulation to an area of termination.

The processes involved in evolving landforms and the process within itself the glacier are termed as the *glacial*. Mechanism involved in the growth of these ice bodies is called glaciations. A glacier can grow where the mass balance (input-*accumulation*) is positive compared to loss (melting-*ablation*).

In general, glaciers are formed in locations where accumulation of snow and sleet exceeds snowmelt over a long duration. Over decades or centuries the accumulation leads to the formation of a glacier due to crystallization of water into rivers of ice. There have been several episodes of waxing and waning in glaciers during recent geological period. Waxing period is termed as *glacial*, whereas, the time period when glaciers are in the negative phase (waning) of mass balance is known as *inter-glacial*. Some glaciers have a special type of movement called "surge". This can be defined as alternating period of slow and rapid movement. Usually over long periods the movement is slow to transport the mass surplus from the upper part of the glacier down to the lower part. The lower part of the glacier then appears to be decreasing and the glacier tongue retreating. Suddenly the glacier starts to move at a speed many times higher than normal (normally tens of meters to kilometers in a day), pushing forward in to lakes and moraines developed earlier. Surging glaciers have normally been associated with the Polar Regions and cold glaciers. In the recent years, the increased melting has been clubbed with the increased anthropogenic activities. Glaciers are one of the most sensitive indicators of climate change. Therefore, snow, glaciers and permafrost regions are especially sensitive to the change in atmospheric condition.

A glacier sustains where ambient climate allows deposition of more snow in an area than what melts away during certain period (i.e., accumulation and ablation periods). When this snow pack increases in thickness, a transformation of snow takes place, and the density increases gradually until ice is attained at a density somewhat below 0.9 gm/cm^2. The time needed for this transformation or metamorphosis depends on amount of snowfall and snow melt that occurs on a yearly basis spanning over several decades or centuries. When the total mass of snow and ice thickens, it starts to slide down the natural gradient due to its accumulated mass and gravity. This movement is partly due to sliding at the bed and partly due to internal deformation. The relative proportions change from one glacier to the next, depending upon several parameters such as topography, ambient climate (micro-climate) and ice temperature.

Glaciers still hold over 70% of freshwater reserve on the terrestrial world. The 20th century has seen glacial fluctuations on the global scale. This has been a period of dramatic glacial retreat in almost all alpine regions of the world. The first phase of this glacier retreat was associated with termination of the Little Ice Age that ended in the 19th century (supposed to have ended in the 1850s). The retreat corresponds with a warming of 0.3°C in the first half of the 20th century in the northern hemisphere. In the last 25 years, a second 0.3°C warming has caused northern hemisphere temperature to rise to unprecedented level compared to the last 1000 years (WWF, 2005). Global mean surface temperatures have risen by 0.74°C ± 0.18°C when estimated by a linear trend over the last 100 years (1906–2005). The rate of warming over the last 50 years is almost double than over the last 100 years (0.13°C ± 0.03°C vs. 0.07°C ± 0.02°C per decade) (IPCC, 2007). On the Indian subcontinent, temperatures have been predicted to increase between 3.5 and 5.5ºC by 2100 (IPCC, 2001a), and an even greater increase is predicted for the Tibetan Plateau (Lal, 2003). The warmest years in the instrumental record of global surface temperatures are 1998 and 2005, with 1998 ranking high in one estimate, and 2005 slightly higher in two other estimates (IPCC, 2007). It is estimated that a 1ºC rise in temperature will cause alpine glaciers worldwide to shrink as much as 40 per cent and more than 50 per cent in volume as compared to 1850 (IPCC 2001b).

The Himalayas have the largest concentration of glaciers outside polar caps with a staggering number of 9,575 glaciers within India territory (Raina, 2008). These Himalayan glaciers cater to seven of Asia's great rivers which includes Ganges, Indus, Brahmaputra, Salween, Mekong, Yangtze and Huang Ho. These glaciers are act as source of fresh drinking water to millions of people.

Indus, Ganges and Brahmaputra cater to the livelihood of more than a million households in India. In some states the regional economy is dependent on these perennial rivers. It is estimated that 33,200 km^2 area of the Himalaya is glaciated and these glaciers occupy about 17 percent of the total area of the Himalaya, while an additional area receives snow ranging from 30-40 percent during winter months.

1.2 Classification and Types of Glaciers

Glacier cover of the present day is only a miniscule representative (only 1/3) of the massive *Ice Age* glaciations that covered around 30% of the world surface area. The handiwork of these *Ice Age* glaciations are evident within the landscape of Higher Himalayas.

Occurrence of glaciers is a function of precipitation falling as snowfall and annual rate of melting, which is determined by temperature and nature, type and timing of precipitation. Existence of glaciers is conditioned not only by climate but also by topography and relief, for, there has to be 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; and which does not translate to large scale glacier formation. On the other hand, winter precipitation, however small, is more effective for the growth and sustenance of glacier bodies. Therefore, 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 are classified based on the morphological character, besides temperature conditions as below:

1.2.1 Cirque Glacier

Cirque glaciers are small ice masses generally occupying an amphitheater shaped bedrock hollow, with a width-length ratio of 1:1 (Figure 1, 10).

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.

Figure 1: Cirque Glacier In Milang Valley, Lahaul & Spiti

Source: Field Visit, 2013

1.2.2 Mountain Glacier

Mountain glaciers need not necessarily occupy the same shape as cirques but are elongated, having 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 a better sustenance being at higher altitudes where double-peak effect is pronounced, and with ablation surface strongly restricted (Figure 2, 3, 4 & 10). This type has single arm. Such ice masses may be in large numbers but areal total coverage is always small. These may, at times, cause ice-avalanches. Sometime these are referred to as hanging, niche or glaciers as well.

Figure 2: A Mountain Glacier on The Chandrabhaga (CB) Range

Source: Field Visit, 2013

Figure 3: A mountain glacier on the CB range opposite Rohtang Pass

Source: Field Visit, 2013

Figure 4: A niche glacier on the south-facing slopes of the Great Himalayan tract in Himachal Pradesh

Source: Field Visit, 2013

1.2.3 Mountain Basin Glacier

Mountain basin glaciers are defined as the large ice-bodies that not necessarily occupy valleys but cover large areas in undefined shape in a ratio of 1: 3 or more. These are peculiar glacier feature with two or more tributaries in the higher slopes of the mountains (Figure 5, 10).

Figure 5: Typical mountain basin glacier in Himachal Pradesh

Source: Field Visit, 2013

1.2.4 Ice Cap

Ice caps are on the mountain tops in a sheet-like form (Figure 6, 10). At times, ice caps have radial growth and flow in to either side such as Gangstang glacier in the Chandrabhaga basin. Such ice bodies cover a small fraction of total covered area.

Figure 6: Ice cap in Urgos valley, Miyar basin in Lahaul & Spiti

Source: Field Visit, 2013

1.2.5 Valley Glacier

The valley glaciers flow down in a well-defined terrain which may at times be formed by 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 in to the main trunk glacier. Such glaciers have the largest areal coverage (Figure 7, 8 & 10).

Figure 7: Mulkila valley glacier on the CB range

Source: Field Visit, 2013

Figure 8: Bara Shigri Valley Glacier

Source: Field Visit, 2013

1.2.6 Unclassified/ Rock glacier

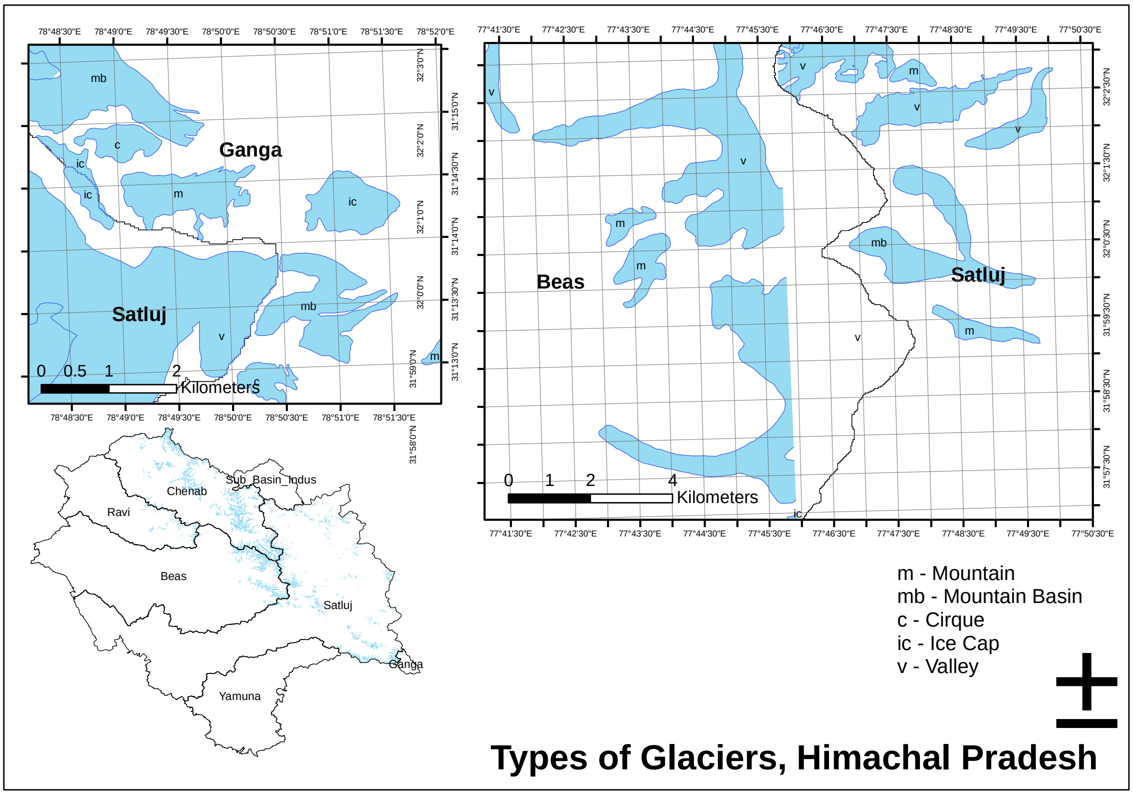
This category of glaciers might not exhibit ice cover at any of its surface but generally are ice-injected and flow in the same manner as the other glaciers (Figure 9, 10). The only difference is the quantity of boulders and sediments which might be as large as 95% of the total size.

These rock glaciers and rock glaciered surfaces are at the transitional zone between the semi-humid Great Himalayan and arid to sub-arid Zanskar range. These have not been taken into account for present analysis.

Figure 9: Rock glacier near the Baralacha Pass

Source: Field Visit, 2013

Figure 10: Type of Glaciers, Himachal Pradesh



Source: TARU, 2013

1.3 Glacier statistics in Himachal Pradesh

The Glacial Lake Outburst Flood (GLOF) is primarily related to the dynamics of glacial lakes; however, it is incomplete without knowing the glacier dynamics in tropical regions such as the Himalaya. Therefore, a detailed glacier inventory is the prerequisite.

The key statistics of inventory created as a part of this study is presented in Table 1, 2 & 3. The inventory was created based on existing catalogue which were validated using high resolution satellite imagery. From the table one can infer that the largest numbers of glaciers in Himachal Pradesh (52.4%) are within the Satluj basin, followed by Chenab (14%), Beas (13.3%) and Ravi (12.8%).

The largest number of glaciers in terms of their type is of mountain glaciers (70.7%), followed by basin glaciers (12.7%) and valley glaciers (9.7%).

Table 1: Basin-Wise Distribution of Glaciers In Himachal Pradesh

Basin	No of Glaciers	Percent
Beas	165	13.3
Chenab	173	14
Ganga	22	1.8
Ravi	158	12.8
Satluj	649	52.4
Sub_Basin_Indus	67	5.4
Yamuna	5	0.4
Total	**1239**	**100**

Table 2: Types And Number of Glaciers In Himachal Pradesh

Type	No of Glaciers	Percent
Cirque	15	1.2
Ice Cap	71	5.7
Mountain	876	70.7
Mountain Basin	157	12.7
Valley	120	9.7
Total	**1239**	**100**

Table 3: Basin-Wise Type and Number of Glaciers in Himachal Pradesh

Glacier Type		Frequency	Percent
Cirque	Beas	2	13.3
	Chenab	1	6.7
	Ganga	2	13.3
	Ravi	2	13.3
	Satluj	8	53.3
	Total	15	100
Ice Cap	Beas	3	4.2
	Chenab	1	1.4
	Ganga	2	2.8
	Ravi	4	5.6
	Satluj	54	76.1
	Sub_Basin_Indus	7	9.9
	Total	71	100
Mountain	Beas	125	14.3
	Chenab	89	10.2
	Ganga	15	1.7
	Ravi	123	14
	Satluj	470	53.7
	Sub_Basin_Indus	49	5.6
	Yamuna	5	0.6
	Total	876	100
Mountain Basin	Beas	22	14
	Chenab	42	26.8
	Ganga	2	1.3
	Ravi	20	12.7
	Satluj	60	38.2
	Sub_Basin_Indus	11	7
	Total	157	100
Valley	Beas	13	10.8
	Chenab	40	33.3
	Ganga	1	0.8
	Ravi	9	7.5
	Satluj	57	47.5
	Total	120	100

The highest elevation of glacier origin varies between ~6,585 meters to ~4,159 meters above sea level, and the lowest terminal point for these glaciers vary between ~6313 meters to ~3625 meters asl (Table 4).

Table 4: Altitudinal Range and Total (In 2d & 3d) Areal Expanse of Glaciers in Himachal Pradesh

Description	No of Glaciers	Elevation Maximum	Elevation Minimum	Glaciar Area 2D (sq km)	Glacier Surface Area (sq km)
No. of Glaciers	1239	1239	1239	1239	1239
Mean	-	5519.54	4957.17	1.88	2
Range	-	2425.9	2687.7	124.03	127.96
Minimum	-	4158.6	3624.9	0.04	0.04
Maximum	-	6584.5	6312.6	124.07	128
Sum	-	-	-	2328.53	2472.49

1.4 Data Base

1.4.1 Primary data

Selected field-checks were carried out in the Beas, Chandrabhaga, Ravi, Yunam and Spiti Basins. These field visits included collection of primary data, wherever ice bodies are present in varied forms and dimensions. Also photographs and other information such as reminiscences of the local populace (*village Naingar, Thirot Nullah L & S*) were collected. These information were used to verify potential glacial lakes (Henderson, 1859).

1.4.2 Secondary sources

Data on type, characteristics, and weather elements are limited for individual glaciers in the Himalayas. Difficult terrain conditions, in addition to high altitude and inaccessibility until recently have restricted any comprehensive study on the glaciers or the glacial lakes in the state of Himachal Pradesh. Further, there is limited availability of long-term of cloud field records or photographs for comparative study baring few, that includes Sonapani (Walker & Pascoe,1906) and few travelogues of British India (Egerton, 1864). Satellite imageries of comparable scales and quality are also nonexistent; hence imageries of only recent years were considered within this study to maintain consistency. Seasonality of images were maintained to ensure comparability. In the absence of necessary base data, proxy methods were incorporated.

The data used within this study are listed below:

- LANDSAT, ETM+, WRS-2, (2005 and 2006)
- LANDSAT, TM, WRS-2, (2010 to 2012)
- Cloud free Image Mosaic (Through WMS services of ArcGIS, QGIS and GE):
- Quick-bird Imageries (Ranging from 2003-2010 at 2.4m resolution)
- SPOT 4 and 5, Panchromatic (of 2011 and 2012 at 10m resolution)
- Topographical sheet, 1:50,000, Survey of India.
- Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER), 16 bit, version 2, (30 m resolution)
- Shuttle Radar Terrain Mapper (SRTM, 2000) for elevation data (90 m resolution).
- Temperature and precipitation data for Udaipur and (1975-2010).

Chapter 2: Methodology

The methodology used within this study was modified from widely accepted methodologies of Campbell (2005) and Mool *et al.*, (2007) which were tested in Nepal and Bhutan Himalayas. The methodology has been modified to contextualize the study to Himachal Pradesh and incorporate some advance techniques of remote sensing and information generation (Figure 11).

Both digital and manual/visual Identification methods were used for capturing database for Glaciers and lakes. The Himalayan glaciers do not have same spectral signature throughout its extent due to debris cover, hence it is essential to identify these both by digital and manual methods. In digital method, unsupervised classification and NSDI (Normalized Differential Snow Index) was used to classify snow area. From the digitally classified data, glaciers were identified and classified using expert knowledge. The identification of glaciers were done using the following indicators using high resolution imageries: topography, highest point (bergschrund) and lowest point (snout-water emanating point).

Lake includes all type of lakes, both natural or man-made. In this study, lakes that have glacier origin were considered for GLOF analysis. Whereas, other lakes (including artificial lakes) may add-on to the catastrophic event associated with GLOF incidence.

2.1 Classification of Lakes

- Moraine-dammed lakes- includes end moraine lakes and lateral moraine lakes.
- Blocked lakes- These are formed through glaciers and other factors, including the main glacier blocking the branch valley, blockade by moraines, glacier tributary blocking the main valley, and the lakes formed through snow avalanche, collapse, and debris flow blockade.
- Supraglacial lakes- lakes formed on top of the glacier surface.
- Cirque lake- are in the palaeo-cirques of the glaciers
- Valley lakes- found in the main river valley

2.2 Area of the Glacier and lakes

Area of the glaciers is provided in square kilometers; measured both in 2-D and 3-D surfaces, whereas area of lakes are the water spread area in 2-D; on the high resolution satellite images.

2.3 Latitude and Longitude

The geographical locations of the glaciers and lakes are provided as Latitude and Longitude.

2.4 Elevation of the Glaciers and lakes

Glacier elevation were divided into highest elevation (the highest elevation of the crown of the glacier i.e. bergschrund), mean elevation (the arithmetic mean value of the highest glacier elevation and the lowest glacier elevation), and lowest elevation (elevation of the glacier tongue/snout). The elevation of lake used relates to the mean sea level.

2.5 Depth of lakes

The depths of glacial lakes were derived using two methods. The one being the difference of highest and the lowest elevation point within the lake area from DEM data acquired by Synthetic Aperture Radar (SAR) imageries. Another method of depth estimation used within this study was using the empirical formula by Huggel (2002).

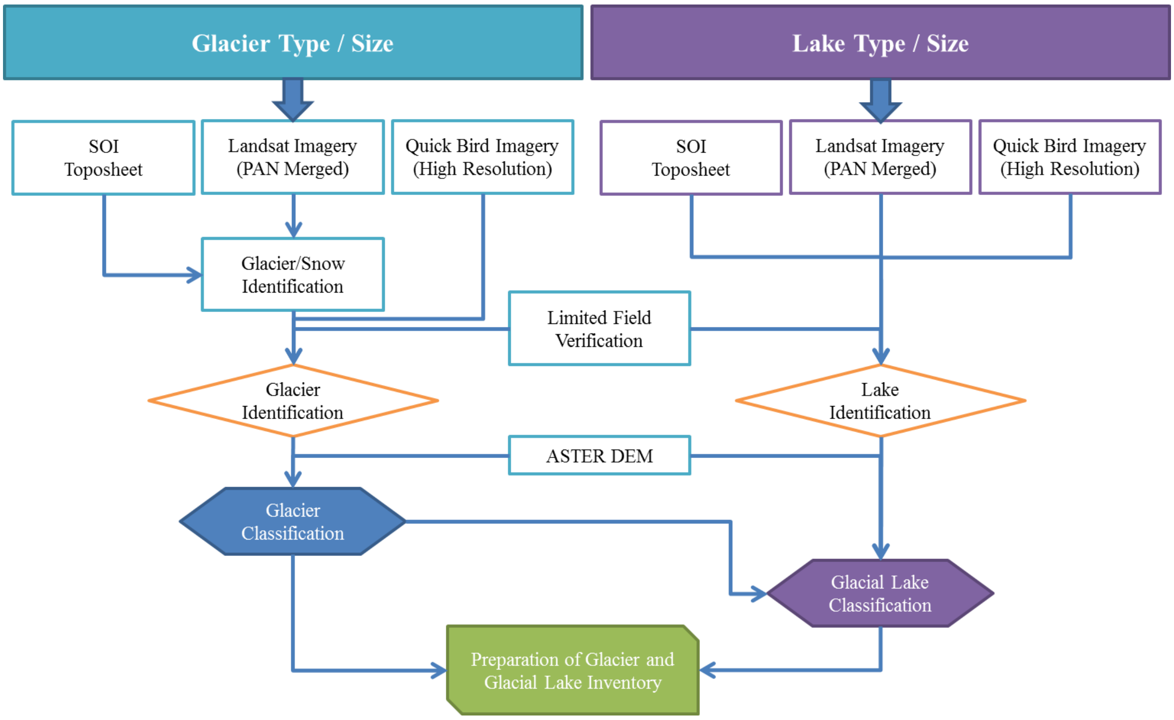
2.6 Volume of lakes

The Volume of Glacial Lakes has been estimated using empirical formula by Evan (1986) and Huggel (2002).

2.7 Watershed Potentially Dangerous Glacial lakes

The catchment areas of potentially dangerous glacial lakes are calculated in sq kms.

Figure 11: GLOF Methodology



Chapter 3: Lake and GLOF Inventory

3.1 Introduction

Periodic or occasional release of large amount of stored water in as catastrophic outburst flood is widely referred to as a *Jökulhlaup* (Iceland), a *debacle* (French), an *aluvion* (South America), or a *Glacial Lake Outburst Flood* (GLOF) in the Himalayas (Mool et at, 2007). Irrespective of nature and type of cause of such flood, these are extensively damaging. A GLOF on the other hand is a catastrophic discharge of water from a glacial lake, be it pro, supra or moraine dammed that mobilizes large boulder and ice downstream as a gush. Much of the damage created during GLOF events is associated with the large amounts of debris and washed out material such as trees and huge boulders. These GLOF events, however infrequent, are severe geomorphological hazards where such floodwaters simply wreak havoc on all human structures kilometers downstream. One of such floods in the Chandrabhaga River is recorded to have damaged all bridges, even beyond the present national borders in 1850s, emanating from Bara Shigri Glacier Lake breaching (Henderson 1859; Egerton, 1864). Therefore, GLOFs in the present context need careful and precise assessment for monitoring and hazard mitigation.

3.2 Glacial Lake Formation

It is necessary to understand the process of formation of glacial lakes while attempting to understanding outburst potential and consequent floods. Glacial lakes are moraine dammed, supra-glacial, sub-glacial, pro-glacial and ablation valley types. The causes of glacial lake formation are mainly moraine damming the glacial-melt waters, temperature rise, surge and glacial dynamics. It is not just the temperature rise that leads to formation and enlargement of glacial lakes but also the temperature drop that might result in bulldozing pro-glacial and ablation valley lakes by enlargement of glaciated area, leading to catastrophic breaches. The Himachal Himalaya has previous records of both these types of GLOFs (Coxon et al, 1996).

3.2.1 Geothermal Conditions

Formation of glacial lakes at high altitudes is a common occurrence where all around thick spread of ice and snow remains but melts only during the ablation season. Geothermal and geomorphological conditions, clubbed with global warming are supposed to be major causes of formation of glacial lakes.

3.2.2 Global Warming

In the ever-expanding industrialized world, warming caused by anthropogenic activities is thought to be the main cause for accelerating glacier melt which causes volumetric increase of water in the associated lakes. In turn, gradual increase in lake water increases the potential of outbreak of the glacial lake once the resistivity of holding material is crossed. However, no studies have been carried out in the Indian Himalayas on such breaches due to the infrequent nature glacial lake outburst floods (GLOF) baring the recent one (Ives, 1986; Dobhal et al, 2013).

It is generally believed that rise in atmospheric temperature happens due to continuing emissions of carbon dioxide (CO_2) and other GHG gases that result in the 'greenhouse effect' on the Earth's surface. Such '*GHE'* is considered to be the catalytic driver of 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).

3.2.3 Glacier Retreat

A sequel to present global warming is the retreat of glaciers in many mountain regions. During the 'Little Ice Age' (AD 1550-1850s), many glaciers grew much larger than what they are today. Large moraines formed in front of the glaciers as a result of this advance which have now got blocked by retreating glacier melt waters, forming pro-glacial, supra-glacial and moraine dammed lakes. Glacials and inter-glacials are cyclic episodes that have occurred several times during at least two-million years or so. But the necessity of assessment of failures of these lakes and subsequent damages to the society and infrastructure demands immediate attention. On an average, glaciers in the Himalayas have retreated by a kilometer since termination of the Little Ice Age; a situation that provides a large space for retaining melt waters to collect, leading to the formation of moraine-dammed lakes (Mayewaski & Jeschke 1979; Sharma & Owen 1996).

3.3 Rise in Water Level in Glacial Lakes

Rise in water level in glacial lakes blocked by moraines creates a situation that endangers to reach a breaching point. The reasons for water level to rise in glacial lakes are as follows:

- Rapid change in climatic conditions increase solar radiation cause rapid melting of glacier ice and snow with or without the retreat of glacier;
- Persistent precipitation events or increase in (rapid) snowmelt;
- Constriction of regular outlet because of re-adjustment of morainic boulders, imbalance in inflow because of sedimentation of silt from the glacier runoff, enhanced by the sand/silt deposit into the lake;
- Blocking of ice conduits by sedimentation or by enhanced plastic ice flow on the supraglacial surface.
- Thick layer of glacial ice (dead ice) weighed down by sediment below the lake bottom on re-settling of iceberg which stops subsurface infiltration or seepage from the lake bottom;
- Shrinking of the glacier tongue in high altitude, causing melt water to accumulate within end moraine complex for increase in proglacial lake;
- Blocking of an outlet by an advancing tributary glacier;
- Landslide at the inner part of the moraine wall, or from slopes above the lake;
- Melting of ice from an ice-cored moraine wall (dead ice);
- Melting of ice due to subterranean thermal activities (tectonics);
- Inter-basin sub-surface flow of water from one lake to another due to height difference and constriction in flow path.

3.4 Bursting Mechanisms

Different triggering mechanisms of GLOF depend on the nature of damming materials, the position of the lake, the volume of the water, the nature and position of the associated mother glacier, physical and topographical conditions, and other physical conditions of the surrounding area. The mechanism of ice core-dammed and moraine-dammed lakes' failure are as under:

3.4.1 Mechanism of ice cored-dammed lake failure

Ice-cored dammed (glacier-dammed) lakes drain mainly in two ways;

- Through (*Moulin*) or underneath the ice
- Over the ice

3.4.2 Ways of initiation of opening within or under the ice dam (Glacier)

- Flotation of the ice dam (a lake can only be drained sub-glacially if it can lift the damming ice barrier sufficiently for the water to find its way underneath).
- Pressure deformation (plastic yielding of the ice dam due to a hydrostatic pressure difference between the lake water and the adjacent less dense ice of the dam; outward progression of cracks or crevasses under shear stress due to a combination of glacier flow and high hydrostatic pressure).
- Melting of a tunnel through or under the ice.
- Drainage associated with tectonic activity.
- Water overflowing the ice dam generally along the lower margin.

The bursting mechanism for ice core-dammed lakes can be highly complex and involve most or some of the above-stated hypothesis. A landslide adjacent to the lake and subsequent partial abrasion on the ice can cause the draining of ice cored-moraine-dammed lakes by overtopping as the water flows over, the glacier retreats, and the lake fills rapidly (Watanbe and Rothacher, 1994).

3.4.3 Mechanism of moraine-dammed lake failure

Moraine-dammed lakes are generally drained by rapid incision of the sediment barrier by outpouring waters. Once incision begins, the hustling water flowing through the outlet can accelerate erosion and enlargement of the outlet, setting off a catastrophic positive feedback process resulting in the rapid release of huge amounts of sediment laden water. The onset of rapid incision of the barrier can be triggered by waves generated by glacier calving or ice avalanching, or by an increase in water level associated with glacial advance (Watanabe et.al, 2009).

3.4.4 Causes of moraine dam failure

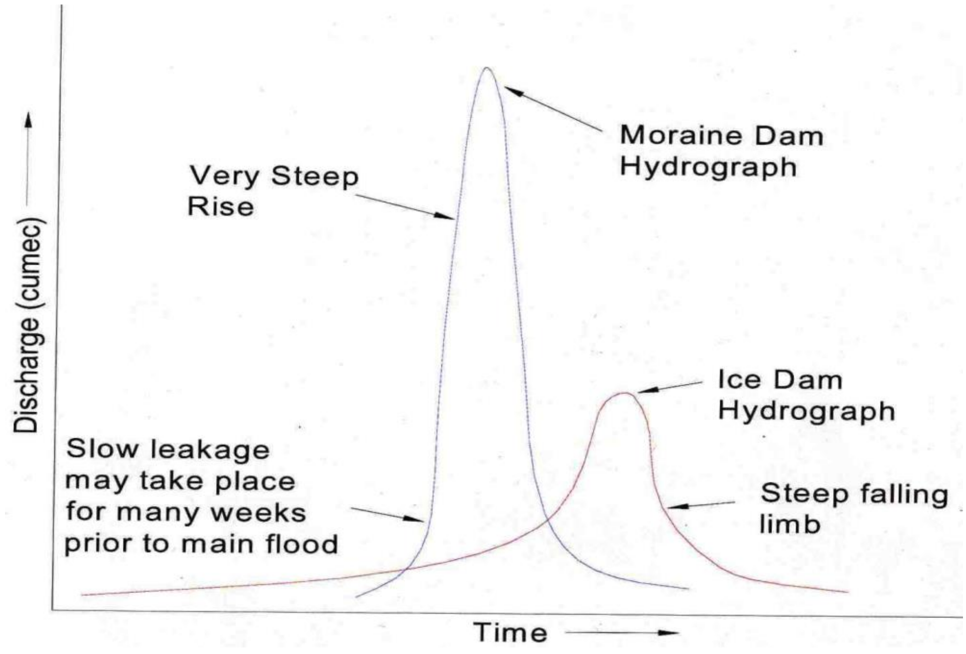
As the impervious ice core within a moraine dam melts lowering the effective height of the dam, it allows lake water to drain over the residual ice core. The discharge increases as the ice-core melts and a greater amount of water filter through the moraine, carrying fine material. The resulting retrogressive erosion of the moraine dam ultimately leads to its failure. In other words, water in or at the bases of the moraine could erode backwards into the moraine dam and further destabilize already weak moraine dams. Potential instabilities of the dam body could further lead to accelerate this process and finally erode or collapse the top of the moraine dam.

Lake water is displaced by the sudden influx of rock and/or ice avalanche debris. The resultant waves overtop the freeboard of the dam causing regressive and eventual failure. Earthquake shocks can cause settlement of the moraine sediments. This reduces the dam to a point that the lake water drains over the moraine and causes regressive erosion and eventual failure.

A receding glacier with a terminus grounded within a proglacial (*end moraine dammed*) lake, can have its volume reduced without its ice front receding up-valley. When the volume of melt water within the lake increases to a point that the formerly grounded glacier floats, an instantaneous sub-glacial drainage occurs. Such drainage can destroy any moraine dam, allowing the lake to discharge until the glacier loses its buoyancy and grounds again. Artificial measures taken to lower the water levels or to change dam structures may trigger catastrophic discharge events.

As GLOFs pose severe threats to human, structures, agricultural fields and natural vegetation, it is important to make reasonably accurate estimate of the likely magnitude of future floods. Several methods have been devised to predict peak discharges, which are the most erosive and destructive phases of floods. The surge propagation hydrograph depends upon the type of GLOF event, i.e. from moraine-dammed lake or from ice-dammed lake. The duration of a surge wave from an ice-dammed lake may last for days to even weeks, while from a moraine-dammed lake the duration is shorter, minutes to hours. The peak discharge from the moraine-dammed lake is usually higher than from ice-dammed lakes, shown in the figure below. Therefore, this study focuses only on the breaching of moraine-dammed (*glacial*) lake (Watanabe et.al, 2009, Campbell, 2005).

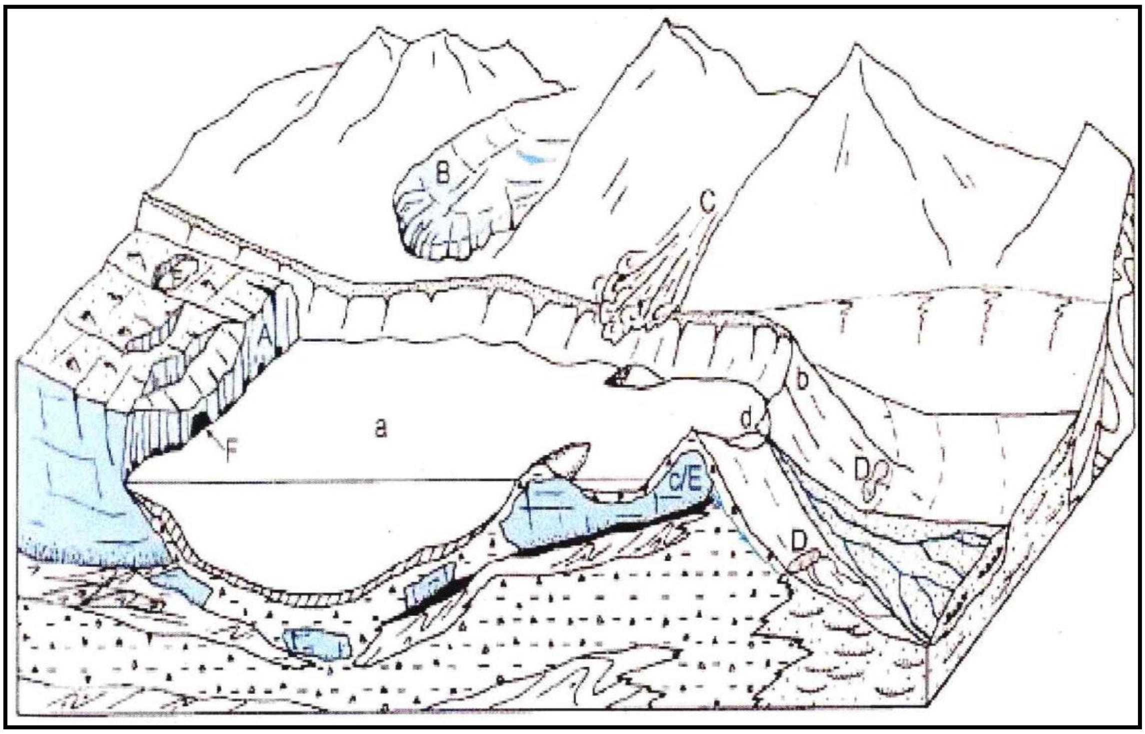
Figure 12: Hydrographs due to Breach of Moraine and Ice-Cored Dammed Glacial Lakes



3.5 Factors contributing to the hazard risk of moraine-dammed glacial lake

(a) Large lake volume, (b) narrow and high moraine dam, (c) stagnant glacier ice within the dam, and (d) limited freeboard between the lake level and the crest of the moraine ridge. A schematic diagram of a hazardous moraine-dammed glacial lake is shown in Figure 13.

Figure 13: Schematic Diagram of A Hazardous Moraine-Dammed Glacial Lake



Source: Dahms, 2006

Potential outburst flood triggers include avalanche displacement waves from

- Calving glaciers,
- Hanging glaciers, and
- Rock falls;
- Settlement and/or piping within the dam (due to progressive seepage or seismic activity);
- Melting ice-core; and
- Catastrophic glacial drainage into the lake from sub-glacial or en-glacial channels or supra-glacial lakes.

Glacier lakes in Hindu Kush Himalaya (HKH) are classified into Erosion lake, valley trough lake, cirque lake, blocked lake, lateral and end-moraine lake and supra-glacial lake (ICIMOD & UNEP 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. Supra-glacial 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 supra-glacial lakes.

Figure 14: Lakes of Himachal Pradesh

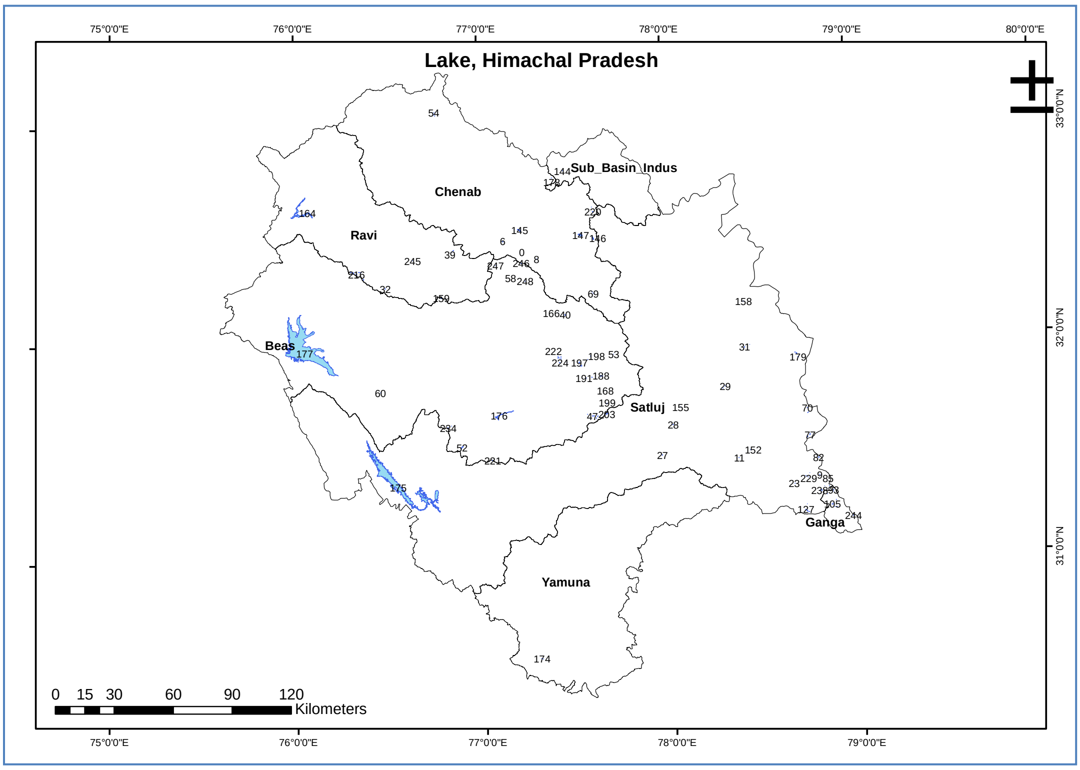


Figure 15: Tarn/cirque Lake of Dashaur above Rohtang Pass

Such lakes are almost the permanent features on deglaciated terrains and have stability unless a catastrophic rockfall or slide over-burdens it

Source: Field Visit, 2013

Figure 16: Blocked Lake of Lamdal on Dhauladhar

Sustenance of such lakes is on snow-melt waters, therefore, are relatively long lasting, depending on seasonal snow-cover in the vicinity

Source: Field Visit, 2013

Figure 17: Palaeo-moraine dammed Lake of Manimahesh on the Pir Panjal range

These lakes now depend on snow melt and seepage water through morainic debris for sustenance

Source: Field Visit, 2013

Figure 18: Thamsar Lake, proglacial moraine dammed lake on the Pir Panjal

Variability in climate parameters will determine their stability

Source: Field Visit, 2013

Figure 19: The Samundri 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 flood on account of increase in volume of water and resultant pressure.

Source: Field Visit, 2013

Figure 20: Avalanche blocked lake in Sonapani/Kulti Valley

These are relatively small in size and exceptionally temporary.

Source: Field Visit, 2013

Figure 21: Rock-glacier dammed lake of Suraj Tal

Such lakes are long-lasting, depending on degree of ice-core of rock-glacier and erosive capacity of the flowing water. However, the blockade resulted in the seepage that reduces the build-up of lake area and pressure

Source: Field Visit, 2013

Figure 22: Pro-glacial Lake of Uldhampu Glacier in Miyar Basin

Such lakes have history of breaching and destroying farmland and bridges in the basin.

Source: Field Visit, 2013

Figure 23: Deepak Tal Lake

Lakes such as Deepak Tal are man-made features, created by blocking spring-water on the morainic deposit. These lakes may not breach as the input remains constant over the years.

Source: Field Visit, 2013

Figure 24: The Chandra Tal Lake

The Chandra Tal, termed as glacial lake, in fact, has evolved along the rock-bar and valley-wall, with water coming in from snow-melt water through seepage. Such lakes on stable landforms are the permanent features until there is rock falls or debris flows into it.

Source: Field Visit, 2013

Figure 25: The catastrophic lake Palaeo

The most catastrophic lakes are formed by glacier surge episodes such as this palaeo-lake deposit of Barashigri Glacier. This glacier (hanging in the middle background) is known to surge and block the river valley and flood almost the entire length of River Chenab

Source: Field Visit, 2013

There are a total of 212 glacial lakes in Himachal Pradesh (Figure 14). Their size, depth and volume have been calculated using DEM and widely accepted empirical formula for the assessment of GLOF. Out of the total, only eleven glacial lakes have been identified as high potential based on the following criteria:

1. *Moraine dammed (High)*
2. *Frequent change in size (High)*
3. *Associated with steep adjacent topography (High)*
4. *Narrow crest width (High)*
5. *Glacier Association; Supra-glacial, Pro-glacial (High)*

Chapter 4: Summary and Conclusions

In Himachal Pradesh (HP), glaciers and ice-bodies cover a total of 2,473 km^2, i.e. 4.44% of the total area of 55,673 km^2 of the state of Himachal Pradesh. All major rivers of HP; namely Sutlej, Beas, Chandrabhaga, Ravi and Yamuna (Chherup) are fed by these glaciers year round. Small portion of the Indus and Ganges basin that flow within Himachal Pradesh also owe its origin to ice-bodies.

Glaciers in the state of Himachal Pradesh (HP) do exhibit secular retreat at varied rates over past one century. Some of these glaciers have retreated to over a kilometer. From the observation, it can be inferred that large glaciers have exhibited measurable frontal changes while smaller glaciers appear to be relatively stable. Given the current situation, future snowfall pattern and temperature will have an impact on the sustenance of glaciers, glacial lakes and ice bodies.

In HP, GLOF has the potential to cause damage to life and infrastructure, with short to medium term impact on livelihood. It has been observed elsewhere that glacial lake outburst floods have cascading effect on life, livelihood and infrastructure. In the state of HP, the local economy and state gross domestic product (GDP) is highly dependent on agricultural, horticulture production and hydropower generation. These activities are in turn dependent on the glacial ice melt and snow melt during summers. Changes in the glaciers or resultant GLOF, may have an impact on the regional economy.

Given the sensitivity of the glaciers to environmental changes induced by the human activity, it is necessary to evaluate and assess glaciers periodically. In this study, high resolution satellite data ~1m and 2.4m spatial scale were used for delineating glaciers and ice bodies

The results indicate that in HP, blocked glacial lake account for 53.8% whereas moraine dammed lakes are only 9.9%. Proglacial and supraglacial lakes account for 17% which are not only unpredictable but also have high potential of breaching in the face of increase in temperature, increased snowmelt or increased liquid precipitation. The Satluj basin contains almost 42% (42.5) of all the glacial lakes of Himachal Pradesh, followed by the Beas basin (25.5%).

It is important to note that in this study, the valley glaciers have been considered as one single system, avoided counting of its tributaries as separate individuals; therefore, providing a total number of 1,239 ice-bodies of various types and dimensions. Also snow-drift deposits are not taken into consideration for any analysis as these are only transitory in nature which may or may not exist from year to year basis.

The statistics and character of the potential glaciers lake with possibility for experiencing breach are represented in Annex (1) and (2). These lakes will require constant monitoring to safeguard their structure and to minimize the impact downstream. The glacier lake types evident in HP and their distribution are provided in Annex (3). Annex (4) presents the basin-wise distribution of glacial lakes.

Chapter 5: References

Campbell, G.J. (2005). Inventory of glaciers, glacial lakes and the identification of potential glacial lake outburst floods (GLOFs) affected by global warming in the mountains of India, Pakistan and China/Tibet Autonomous Region, Overview of project work and outcomes: non-technical summary of APN Project 2004–03, pp.48.

Coxon, P, Owen, L & Mitchell, W.:1996, Late Quaternary catastrophic flood in the Lahul Himalaya. Journal of Quaternary Science, 11/6, 495-510.

Dobhal, D.P., Gupta, A.K., Mehta, M. & Khandelwal, D.D. (2013). Kedarnath disaster: facts and plausible causes; Current Science, Vol 105, No 2.

Egerton, G.N. (1864), “Journal of Tour Through Spiti, London, Cundall Downes.

Evans, S.G. (1986), The maximum discharge of outburst floods caused by the breaching of man-made and natural dams. Cana-dian Geotechnical Journal, 23: 385–387.

Hegglin, E. and Huggel, C.:2008, ‘An integrated assessment of vulnerability to glacial hazards: a case study in the Cordillera Blanca, Peru’, Mountain Research and Development , 28(3/4), 299-309.

Henderson, A.: 1859, Memorandum on the nature and effects of the flooding of the Indus. Jour Asiatic Soc Ben, Vol 28, 199-228.

Huggel, C., Haeberli, W., and Kääb, A. 2000. Compilation of histor-ical data as a basis for analyses of glacier floods and ice ava-lanches in the Swiss Alps. In Proceedings of the European Geophysical Society (EGS) 25th General Assembly, Nice, 24–29 April 2000. Abstracts, Vol. 2

Ives, J.D. (1986), Glacial Lake Outburst Flood and Risk Engineering in Himalaya, ICIMOD, Occasional Paper, 5, 42, pp

Kääb, A., Huggel, C., Paul, F., Wessels, R., Raup, B., Kieffer, H. and Kargel, J. (2003). Glacier monitoring from ASTER imagery: accuracy and applications, EARSEL eProceedings, 2, pp.43–53.

Lal M (2003) Global climate change: India’s monsoon and its variability. J Environ Stud Policy 6:1–34

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

Mool P., ICIMOD (2007), "Glacier Lakes and Glacial Lake Outburst Flood Events in the Hindu Kush-Himalayan Region", E-conference on climate change and the Himalayan Glaciers

Mool, P.K., Bajracharrya, S.R. & Joshi, S.P. (2007). Inventory of glaciers, glacial lakes, glacial lake outburst floods: monitoring and early warning systems in the Hindu Kush-Himalayan Region, Nepal, Kathmandu, ICIMOD, pp.386.

Owen, L.A., Benn, D.I., Derbyshire, E., Evans, D.J.A., Mitchell, W., Sharma, M., Thompson, D., Lloyd, M. & Richardson, S. (1996). The Quaternary glacial history of the Lahul Himalaya, Northern India, Journal of Quaternary Science, 11, pp.25-42.

Raina, V. K. and Srivastava, D. (2008), "Glacial Atlas of India", Geological Survey of India, Banglore

Sharma, M.C. & Owen, L.A. (1996). Quaternary glacial history of the Garhwal Himalayas, India, Quaternary Science Reviews, 15, pp.335–65.

Shrestha,A.B., Eriksson,M., Mool,P., Ghimire,P., Mishra,B. and Khanal,N.R.:2010, 'Glacial lake outburst flood risk assessment of Sun Koshi basin, Nepal', Geomatics, Natural Hazards and Risk, 1(2), 157–169.

Walker H and Pascoe, E.H.: 1907, Notes on certain glaciers in Lahaul, Rec. Geol. Surv. Ind, 35 (4), pp 139-147.

Watanabe,T., Lamsal,D. and Ives,J.D.:2009, 'Evaluating the growth characteristics of a glacial lake and its degree of danger of outburst flooding: Imja Glacier, Khumbu Himal, Nepal', Norsk Geografisk Tidsskrift-Norwegian Journal of Geography, 63, 255-267.

Watanbe T. and Rothacher D. " The 1994 Lugge Tsho Glacial Lake Outburst Flood, Bhutan Himalaya Mountain Research and Development, Vol. 16, No. 1 (Feb., 1996), pp. 77-81

WECS (1987)a, Erosion and sedimentation in Nepal Himalayas; an Assessment of river provess, WECS Report No. 4/3/010587/1/11, seq. No. 259, Kathmandu, Nepal.

WWF (2005), 'An overview of glaciers, glacier retreat, and subsequent impacts in Nepal, India and China', (This overview report is the product of a regional level project 'Himalayan glaciers and river project'), WWF Nepal Program.

Web Sources:

http://www.ipcc.ch/publications_and_data/ar4/syr/en/contents.html

Annexure

Annex 1: Glacial Lakes with Potential Risk of Breaching

Lake No.	Longitude	Latitude	Elevation (m)	Toposheet No.	Basin	Type
70	78.7416	31.6784	5,530	53I10	Satluj	Supraglacial
145	77.2181	32.5266	4,064	52H2	Chenab	Proglacial
147	77.5481	32.4986	4,155	52H11	Chenab	Proglacial
213	76.3586	32.3436	3,938	52D7	Ravi	Proglacial
215	76.3466	32.3452	4,092	52D7	Ravi	Proglacial
216	76.3332	32.3359	3,973	52D7	Ravi	Proglacial
217	76.3719	32.3125	4,157	52D7	Ravi	Proglacial
220	77.6178	32.6045	5,198	52H10	Chenab	Supraglacial
229	78.7577	31.3534	5,352	53I15	Satluj	Proglacial
238	78.7950	31.2976	5,455	53I15	Satluj	Proglacial

Annex 2: Glacial Lakes with Potential Risk of Breaching

Lake No	Lake Area (Sq m.)	Depth (m) DEM	Depth (m) Huggel	Volume 1 (cum) Huggel	Volume 2 (cum) Evans	Watershed Area (Sq km)
70	11,496	15	5	60,677	43,142	1
145	6,42,070	30	29	1,83,56,952	1,80,07,022	49
147	11,92,328	20	37	4,42,09,480	4,55,68,189	154
213	11,785	10	5	62,855	44,780	0
215	20,060	5	7	1,33,764	99,440	0
216	75,356	17	12	8,76,075	7,24,012	0
217	33,402	14	8	2,75,918	2,13,657	0
220	54,428	31	10	5,51,948	4,44,425	1
229	27,141	14	8	2,05,480	1,56,493	0
238	12,600	12	5	69,109	49,499	0

Annex 3: Type-Wise Distribution of Glacial Lakes

Type	No. of Lakes	Percent
Blocked	114	53.8
Cirque	23	10.8
Moraine Dammed	21	9.9
Proglacial	22	10.4
Supraglacial	14	6.6
Valley	18	8.5
Total	212	100

Annex 4: Basin-Wise Distribution of Glacial Lakes

Basin	No. of Lakes	Percent
Beas	54	25.5
Chenab	15	7.1
Ganga	24	11.3
Ravi	26	12.3
Satluj	90	42.5
Sub_Basin_Indus	1	0.5
Yamuna	2	0.9
Total	212	100

Annex 5: HP Lake Summary Statistics

Description	Elevation (m)	Lake Area (sq m)	Depth (m) DEM
Number of Lakes	212	212	212
Mean	4,524	16,42,489	9
Range	5,157	21,01,01,762	155
Minimum	393	53	0
Maximum	5,550	21,01,01,815	155
Sum	-	34,82,07,585	1,890

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