Glacier Inventory and Hazard Zonation of Moraine Dammed Lakes in Eastern Himalayan Region

Synopsis

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Submitted By

Vanya Bajpai

Under the Supervision of

Prof. Rolee Kanchan

Department of Geography, Faculty of Science

The Maharaja Sayajirao University of Baroda

Vadodara – 390002 (Gujarat)

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Chapter 1:

1.1 Origin of the Research Problem:

Glaciers are commonly conceived as a mass of ice that travels gradually down a slope. They are primarily composed of ice crystals, water and rock debris, with ice being the most important component. The glaciers of the Himalayan Region are the Valley Glaciers whose movements are controlled by the valley structure and driven by the region's terrain. These glaciers are formed on relatively gentle slope of high mountainous terraces, thus the glaciers flow from the ice fields to the valleys. Temperature has a considerable influence on the morphological behavior of glaciers. Glaciers adapt quickly to minute changes in local climate (Oerlemans, 2005) by altering their mass balances, which influences their sizes and this can be used as an indicator for climate change (Nesje and Dahl, 2000). Therefore, many paleo-climatic inferences are based on the location of their moraines (Refsnider et al., 2007). Another important feature of the glaciers are the Moraine Dammed Lakes which are a result of the glacier melt. The fast retreat of glaciers over the last decade has resulted in rapid accumulation of melt water in most moraine-dammed lakes of the various basins. It has boosted their potential energy while decreasing the damming material's shear strength (Bajracharya and Mool, 2009). The loose-moraine dam will eventually fail, resulting in a GLOF (Glacier Lake Outburst Flood) (Ives, 1986; Zimmermann et al., 1986; Yamada, 1998; Richardson and Reynolds, 2000; Mool and others, 2001; Kattelmann, 2003). As a result, glacier observations may aid in answering many unresolved concerns about climate change. Therefore, this study was undertaken to contribute to the the glacier database for future investigations.

1.2 Research Framework:

Available Resources and Literature Review:

Earlier many methods have been devised for studying the glaciers and making their inventories. Floods caused by the Kumdan glaciers in the upper Shyok valley, Ladakh, Jammu & Kashmir is the earliest record (1780) of glacier observation, in the Himalayas. It was followed by, publication on Indian glaciers by the Geological Survey of India in 1895 which was a detailed report on Machoi glacier, Jammu & Kashmir. The databases which exist are GLIMS (Kargel et.al. 2014), ICIMOD, GlobGlacier (Paul et. al., 2009).

GLIMS database includes the World Glacier Inventory (WGI/WGMS (1989)) (Haeberli, et. al., 1989). It contains information for over 130,000 glaciers and includes parameters like geographic location, area, length, orientation, elevation and classification. The WGI is based primarily on aerial photographs and maps with most glaciers having one data entry only. They have now also included use of satellite data (LANDSAT, ASTER) for glacier mapping. Similarly, ICIMOD database also shares GLIMS format, so that it can be (in future) interoperable with the GLIMS database. GlobGlacier database also utilizes GLIMS data format and their data is mostly already incorporated into the GLIMS database. Likewise, the 2000 Chinese inventory is now part of the GLIMS database and the newer China inventory is being added.

Potentially hazardous lakes are becoming increasingly common as a consequence of climatically driven glacier recession (Richardson and Reynolds, 2000). Lakes can expand rapidly in spaces opening up between receding glacier fronts and terminal moraines, and they are prone to catastrophic drainage if the moraine dam is breached (Clague and Evans, 2000). Lake drainage can have severe impacts on both fragile mountain ecosystems and local economies. In addition to those moraine-dammed lakes currently in existence, many more will form in the coming decades as more glaciers cross the threshold required for rapid lake expansion (Thompson et al., 2012). **G**lacial **L**ake **O**utburst **F**loods (GLOF's) have been recorded in the Himalayas in recent decades. Most of them have been ignored as they happened in uninhabited regions.

However, the known catastrophic outbursts from glacier lakes, as well as meltwater floods and debris flows, have caused severe damage with respect to life and property, farmland, water conservancy, communications, transportation, etc. (Yongjian and Jingshi, 1992). For example, catastrophic outbursts of moraine dammed lake (Chorabari Lake) together with heavy rains on 16^{th} and 17^{th} June 2013 caused flooding of Saraswati and Mandakini Rivers in Rudraprayag district of Uttarakhand.

Susceptible glaciers include those with long, low gradient ablation zones. At present, however, predicting where or when significant hazards will develop is not possible because little is known about the processes and rates of lake expansion.

The focus has been to identify features that glaciers with glacial lakes have in common, thus identifying indicators of future lake development (Suzuki et al., 2007; Sakai and Fujita, 2010). In addition, not all large moraine dammed lakes pose significant hazards, because drainage can occur slowly if the level of the dam is reduced gradually over several years (Hambrey et al., 2008). A much greater understanding of the mechanisms and processes involved in lake formation and expansion is required, therefore, to allow the prediction of potential hazards and to provide timely mitigation.

According to Binay Kumar and T. S. Murugesh Prabhu of Centre for Development of Advanced Computing (C-DAC), lakes in west and north Sikkim are expanding due to accelerated glacial retreat and melting due to climate change impact. The lakes have been increasing in size and volume since 1965.

Sikkim is dotted with numerous lakes as observed in the satellite data and have a danger linked with it as Sikkim falls in Zone-IV of the Indian seismic chart and earthquakes may trigger GLOF.

Motivation:

Significance and Justification of the Study:

Several agencies, like GLIMS and ICIMOD, have previously drafted datasets that had some gaps. The present work was inspired by these missing linkages. The following gaps that exist in those databases are as follows:

GLIMS:

1) Elevation histograms were given little consideration (but ICIMOD includes comprehensive histogram data from SRTM).
2) Glacier dammed lakes were not typically arranged into drainage basins and sub-basins (but ICIMOD data are).

ICIMOD:

1) There was no demarcation of accumulation/ablation regions.
2) Dynamic parameters were given little consideration (changes).
3) Uncertainties of boundaries were not emphasised.

Hence, the proposed research attempted to fill in the gaps left by previous inventories.

1.3 Research Objectives:

The objective of this investigation was twofold; firstly it aimed at developing a methodology for inventorying glaciers and mapping various glacier features such as glacier boundary, ice divide, snow/equilibrium line, ablation area, accumulation area and glacier-dammed lakes. The methodology used for this study was inspired by the Himalayan Snow and Glacier Studies, SAC (Space Applications Centre), 2011 where glacier delineation along with the estimates of glacier-stored water had been made for the

Himalayan glaciers. Other than inventorying and mapping the glaciers magnitude to error was also assessed using other datasets like the Google map and the temporal changes were also verified. Secondly, it aims at analyzing the dangers of GLOF (**G**lacier **L**ake **O**utburst **F**loods) through the lakes mapped in the inventory. Finally, Modelling a Hazard Zone for the Moraine Dammed Lakes was done.

1.4 Methods:

The glacier inventory maps were classified and identified using Indian Remote Sensing (IRS) satellite data from 2004 to 2007. Thus, geocoded IRS AWiFs data with five day repeatability on 1:50,000 scale at the end of ablation season (July to September) were procured in digital format from the National Data Centre (NDC), National Remote Sensing Centre (NRSC), Hyderabad. Therefore, to map the glaciological features Conventional Band Combinations of 2 (0.52 - 0.59 µm), 3 (0.62 - 0.68 µm) and 4 (0.77 - 0.86 µm) with an additional SWIR band (1.55-1.70 µm) were used.

In addition to satellite data, ancillary data such as toposheets for the state of Bhutan were obtained from Survey of Bhutan (SOB) topographical maps at 1:50,000 scale and Survey of India (SOI) (Figure 1), trekking routes, guide maps, political maps were needed for the delineation of political boundaries to define the study area and physiographic maps, drainage maps (from Irrigation Atlas of India), basin boundary maps (from Watershed Atlas of All India Soil and Land Use Survey (AIS & LUS), 1970)

The glacier inventory map, which includes information about glacier characteristics, was created using a soft copy of multi-temporal IRS AWiFS and LISS III satellite data and ancillary data where data gaps were there. Spectral reflectances of the accumulation region are high in bands 2, 3 and 4 of IRS AWiFS, LISS II and TM data, according to previous field studies and findings obtained from satellite data. Reflectance in bands 2 and 3 is higher than that of the natural landscape but lower than that of vegetation in band 4. These spectral features can help discern between glacial and non-glacial features.

The first set of satellite data was used to construct provisional glacier inventory maps where the spatial variations of each glacier (with latitude, longitude and elevation) were taken into consideration. Then, using a second set of satellite data, these inventory maps were updated to include all of the essential glacier features that were missing or could not be delineated from the first set of data. Random examinations of glaciers using

LANDSAT data from 2000 to 2021 were carried out for this purpose. Google Maps was also utilized for the same reason. If any modifications were required, they were incorporated into the final glacier inventory maps. The glacier data sheet was developed as a consequence of measurements taken on the glacier inventory map. Furthermore, the Glacial Lakes were mapped and analyzed in this research, therefore the GLOFs were also included in the inventory investigations.

Figure-1 Study Area - Sikkim and Bhutan divided into SOI & SOB Toposheets

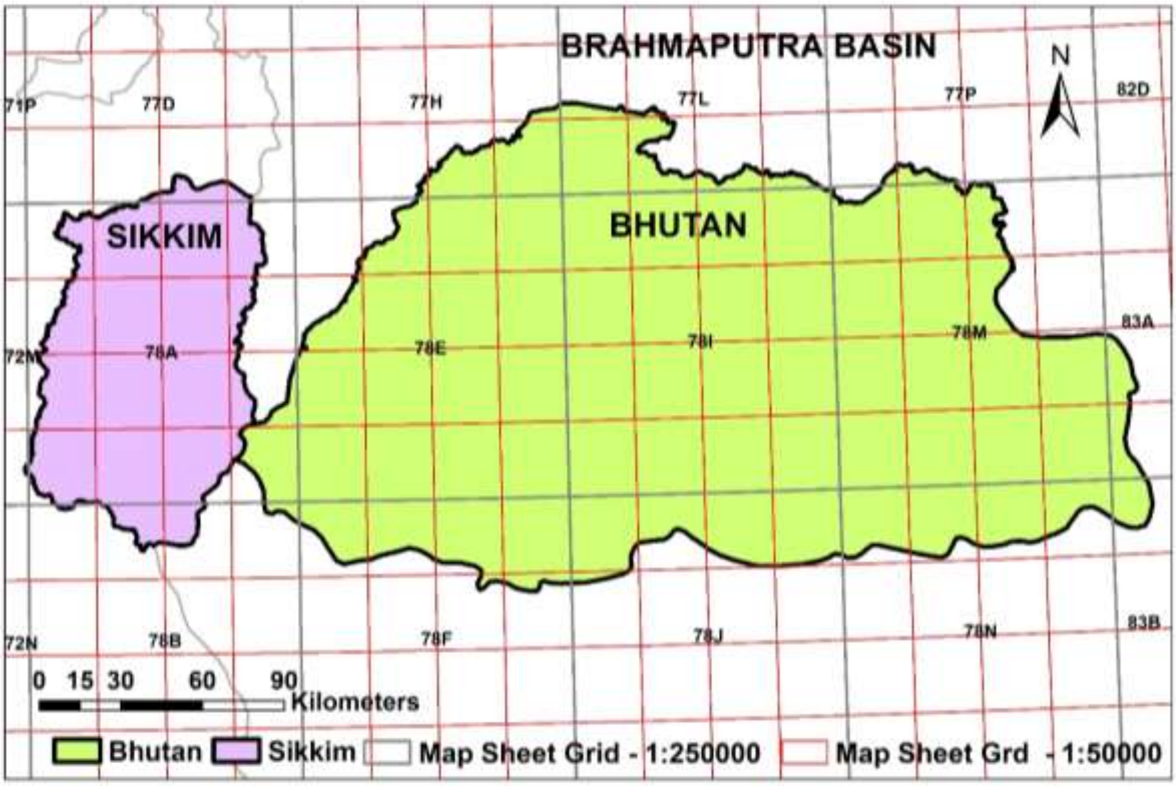
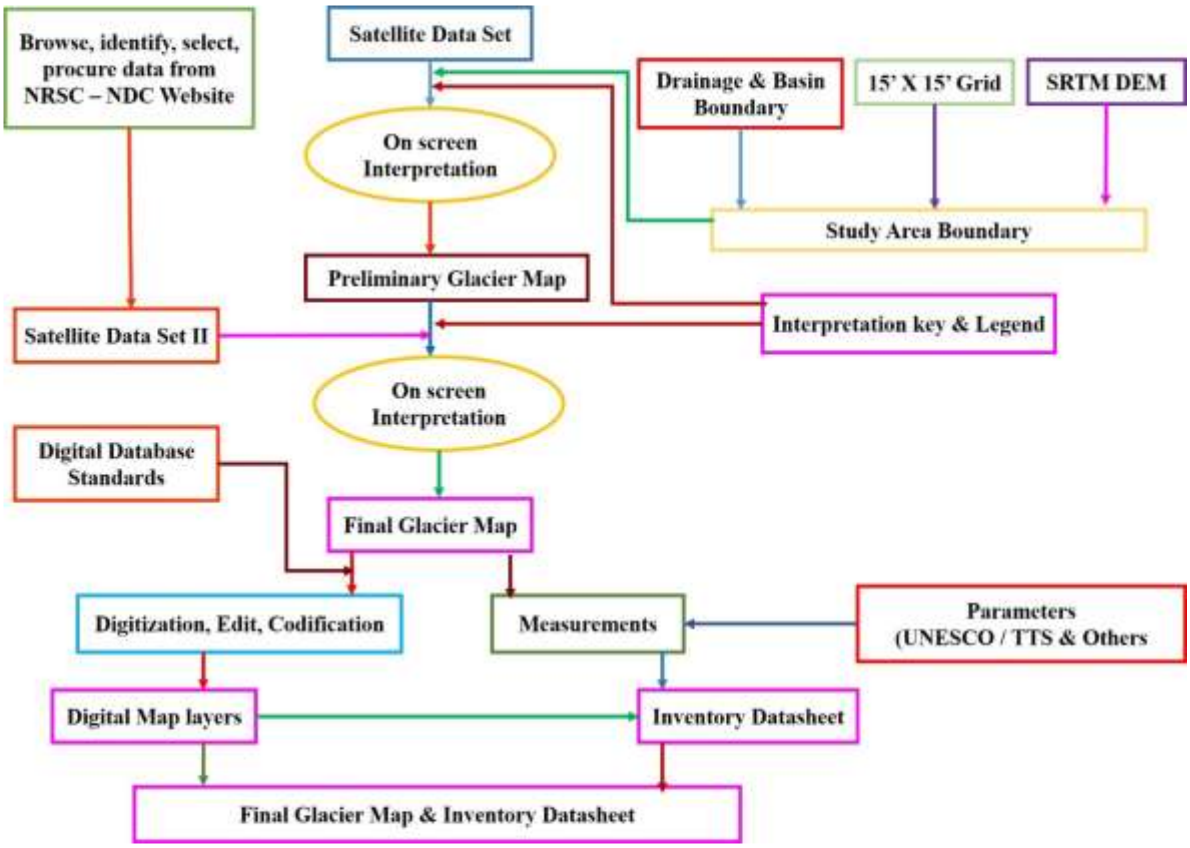


Figure 2 shows a flow chart that shows the broad framework for building a glacier inventory map, data sheet and digital data base (Sharma et al, 2006)**.** For generating a glacier inventory map entails creating and integrating primary theme layers into a GIS.

- **i)** Base detail,
- **ii)** Hydrological information and
- **iii)** Glacier and de-glaciated valley features (Sharma et al, 2008).

Figure 2: Broad approach for glacier inventory map and data sheet preparation



Source – Snow and Glaciers of Himalayas, 2011; Computed

Chapter 2:

2.1 Eastern Himalayas:-

The Eastern Himalayas that extends from 26°40'- 29°30'North and 88°2'- 97°5' East covering an area of about 122,802 square kilometer encompasses the Kingdoms of Sikkim and Bhutan within its territories. Though the North-East Frontier Agency (excluding part of Lohit Frontier district which lies to the south of the Lohit River and Tirap) and Darjeeling district (excluding Siliguri sub-division) of West Bengal are also a part of the Eastern Himalayan region but to be crisp in the division, political boundaries were also taken into consideration (Singh, R. L., 1971). Figure 3 shows the location area map of the study area.

Its distinctiveness as a physical entity is marked by major distinctions in both political and physical features. As a result, the eastern Himalayan realm was divided into three geographic regions:

a) The Darjeeling and Sikkim Himalayas, b) Bhutan Himalayas c) The Assam Himalayas.

Thus, the primary reason for choosing Sikkim and Bhutan as the study region for the current study was that the political divides in the Eastern Himalayas corresponded to the physical divisions.

2.2 Sikkim: -

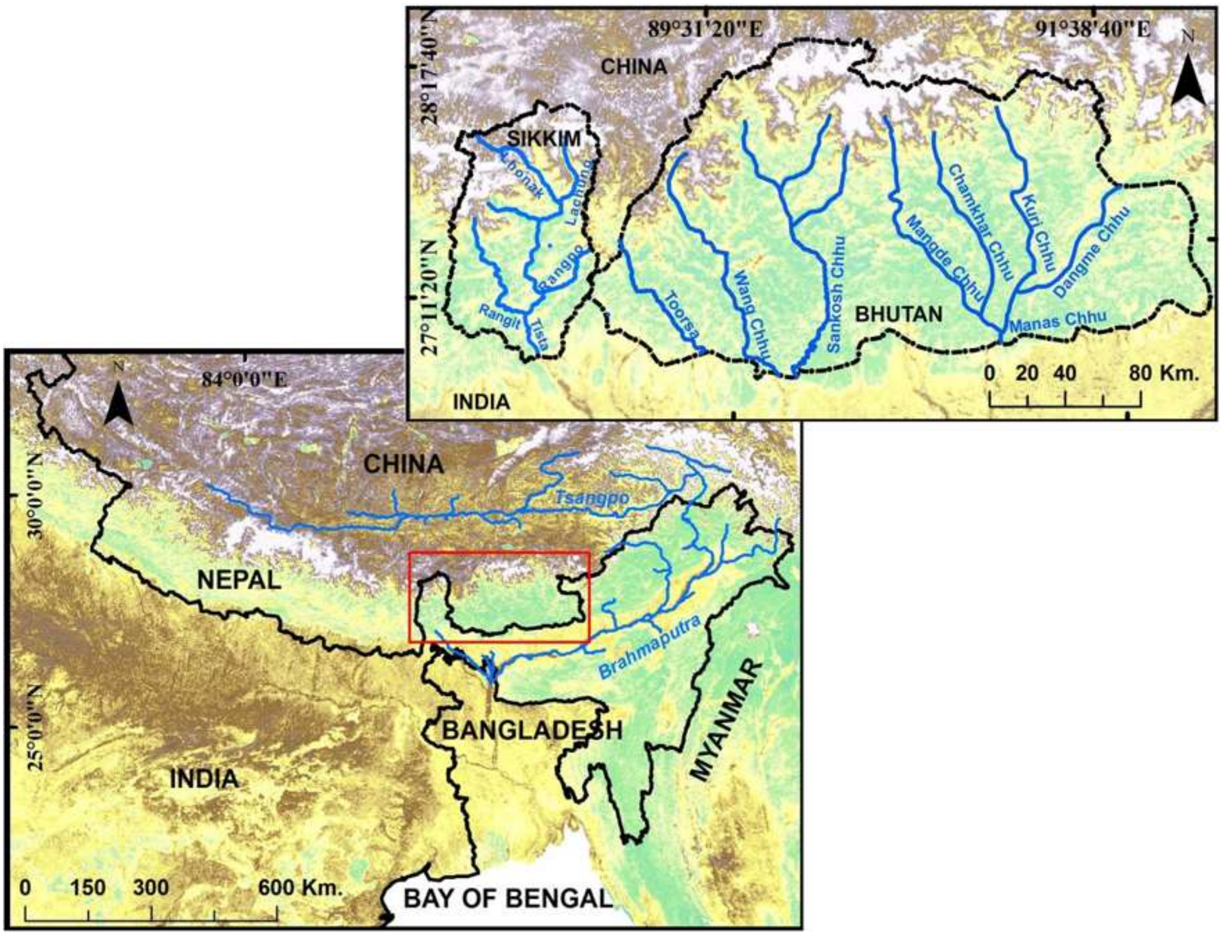
The small state of Sikkim situated in the Eastern Himalayas with a total geographical area of 7096 square kilometer extends between 27° 04' 46" and 28° 07' 48" N latitude and 88° 00' 58" and 88° 55' 25" E longitude. Measuring just 112 kilometer north-south and 64 kilometer east-west, this land locked state has diverse geomorphic setting, ranging from the deep sweltering valleys (300 m) to the lofty mountains like the Kangchendzonga (8585 m). Sikkim shares its borders with Nepal in the west separated by the Singalila range, Tibet (China) in the northeast separated by Chola range and the Kingdom of Bhutan in the southeast. While to the south, the Rangit and Rangpo Rivers form the borders with the Darjeeling district (West Bengal) (Karan et.al, 1963).

2.3 Bhutan:-

The kingdom of Bhutan, known as Druk Yul, Land of Thunder Dragon extending between 27° to 29° north latitudes and 89° to 92° east longitudes is a small landlocked country with rugged terrain surrounded by the Tibetan Region to the north and bordered by the Indian states of West Bengal, Sikkim, Assam and Arunachal Pradesh to the east, west and south respectively. With a geographical area of 40210.63 square km. Bhutan extends 320 kilometre east-west and 150 kilometre north-south. The geomorphic regime of the state is quite undulating; the northern part has the lofty ranges of the Great Himalayas while to the north-west Chomolhari range marks a frontier with the Chumbi valley of Tibet. Seven drainage systems flowing southwards incise through the six major mountain ranges of Bhutan running north to south, roughly parallel to each other. Listing from west to east the rivers which join the mighty Brahmaputra in Assam are - Torsa, Wang Chu, Sankosh, Mangdi Chu, Bumthang Chu, Kuru Chu and Kulong Chu (Fraser et.

al., 2001) (Figure 1). As the horizontal extent of Bhutan is too much, thus, for the present study, Bhutan was divided into east and west parts on the basis of the river basins.

Figure 3. Study Area Location Map



Source - Computed

Chapter 3:

3.1 Glacier Inventory:-

The various satellite sensors have distinct bands, as detailed in earlier chapters. The glacial features are comprehended in the standard FCC (False Color Composite) of Resourcesat-1, which employed a typical combination of wavelength bands 2 (0.52–0.59 m), 3 (0.62–0.68 m) and 4 (0.77–0.86 m) as well as the shortwave infrared (SWIR) band 5 (1.55–1.70 m). With the combination of these bands different Glacial Features were identified and demarcated. They included point features like Snout and Elevation Points of glaciers and lakes; line features like Ice Divide Line, Snow Line and polygon features like Accumulation and Ablation Zones, Moraine Dammed Lakes etc.

3.2 Sikkim Glacier Characteristics:-

The state of Sikkim that corresponds to the Tista sub-basin is covered by approximately 23 topo-sheets from the Survey of India. In this sub-basin, there are 394 large and small glaciers covering an area of 1321.40 square kilometer (Bajpai et. al., 2014). According to Jack D. Ives and Joe Witte, glaciers found in the Northern Hemisphere and south-facing slopes seem to melt more quickly than glaciers with north-facing slopes. This fact also makes the slope direction of the glaciers a very critical parameter to be measured. The orientation of the majority of glaciers in Sikkim is to the east and to the north-east, while a few glaciers still face to the west and south- west. The total accumulation area of the glaciers is 815.67 square kilometer, which is significantly larger than the total ablation area of 491.41 square kilometer including ice exposed and debris-covered regions. While it was measured that the ablation area obscured by debris (355.53 square kilometer) was larger than the ablation area covered by ice (135.88 square kilometer). The key physical characteristics of a debris layer that control heat conduction to the ice-debris interface are thermal conductivity (or thermal resistance) and albedo.

The findings of the inventory were depicted in the final inventory map which also indicate that the glaciers in the western part of the Sikkim/Tista Sub-Basin are larger than those in the eastern part of the basin. The explanation for this observation can be attributed to the fact that most of the high mountain peaks such as Mt. Kanchendzonga (8582 m), Mt. Kabru (7381 m), Mt. Siniolchu (6888 m), Mt. Simvo (6851 m), Mt. Pandim (6736 m), Mt. Rathong (6736 m) and Mt. Kokthang (6145 m) are situated to the west of Sikkim. Thus, giving the glaciers an appropriate environment to form and grow. The average snowline elevation of the Tista sub-basin is 4853 m, falling within the range of the Himalayan snowline between 4800 – 6000 m. which gives us an indicator of the good health of the glacier.

3.3 Bhutan Glacier Characteristics:-

The Kingdom of Bhutan is covered by approximately 79 topo-sheets from the Survey of India. Bhutan has a glaciated area of 3702.33 square kilometer which is approximately 9% of the total area of the study area. Thus an inventory of 1151 glaciers was prepared where glaciers of varying sizes exist ranging from very small "Simple

Basin" glaciers of 0.11 square kilometer to very large "Compound Basins" glaciers of 121 square kilometer. The total accumulation area was recorded as (2229.71 square kilometer) 60.22% of the total glaciated area which was much higher than the total ablation area of the basin i.e. 39.34% (1456.49 square kilometer) of the glaciated region. The ablation area-debris covered i.e. 79.76% (1161.62 square kilometer) was much higher than the ablation area – ice exposed i.e. 20.25% (294.87 square kilometer) pointing towards the overall stability of these glaciers.

Bhutan's glaciers were further subdivided into three smaller geomorphological units (Singh, 2008) for better understanding due to the country's enormous geographic extent and vast elevation disparities. These are namely:

a) Chomolhari-Kulha Gangri Region (North)
b) Trongsa Region (West)
c) Punakha-Thimphu Region (East)

This category aided in comprehending these glaciers in terms of elevation. It described glacier dynamics in terms of size-number ratio. This yielded an interesting result: the Chomolhari-Kulha Gangri region, which is part of the Greater Himalayas of the Eastern Himalayan Region, has the greatest number of glaciers (432) and the largest glacier size (50 square kilometer to121 square kilometer).

Chapter 4:

4.1 Hazard Zonation of Moraine Dammed Lakes

The mapping of the **M**oraine **D**ammed **L**akes (MDL'S) was done for Sikkim and Bhutan glaciers using the satellite data. The width and length of the lakes were calculated. Sikkim and Bhutan both had three Moraine Dammed Lakes each occupying an area of 3.77 square kilometer and approximately 7.91 square kilometer area respectively. To access the danger of these lakes certain parameters had to be calculated, like the valley profile, the length and breadth of the lakes, the moraines etc. The size of the glacier had a very important role to play in the formation of the lakes. Thus proper assessment of the glaciers where these Moraine Dammed Lakes were situated was done. The elevation of these glaciers and the lakes played an important role as they indicate towards the probable temperature of the area. Thus the DEM (**D**igital **E**levation **M**odel) provided the elevation details. Other layers like Depth, Curvature, Volume and Slope Maps were also prepared for the Inverse Distance Weighted Interpolation (IDW) model. For the calculation of

Danger Index temporal data for these lakes was sorted for. Lastly the settlements were mapped to see the distance of villages or towns from these glaciers and lakes to mark the areas that can be affected in future in any incidence of GLOF.

Glacier Lake Outburst Flood Hazard Zonation Maps for both Sikkim and Bhutan show that Lakes 1 and 3 in Sikkim and Lakes 1 and 2 in Bhutan are in the Very High Risk Zones. This result implies that if these lakes breach in the near future, the landscape as well as any settlement falling in the path of flood water flow would be jeopardized. Lake Number 2 in Sikkim and Lake Number 3 in Bhutan, on the other hand, are in the High Risk Zone in the event of GLOF. When compared to the MDLs of Sikkim, the area of lakes in Bhutan increased significantly. Two of these lakes, Lake 3 from Sikkim and Lake 1 from Bhutan, grew in size the greatest and were orientated to the northeast. These findings necessitate more investigation since these lakes and the glaciers that sustain them are at the highest elevation of all of the lakes studied.

Chapter 5:

5.1 Discussion and Suggestion:-

Glacier Inventory of the Eastern Himalayan region represented the glacial status of the time when the glaciers were mapped. It was a compilation digital vector lines, points and polygons in the form of separate layers. Compilation and calculation of various glacial parameters like orientation, dimensions and area calculations for ablation areas, accumulation zones, supra glacial lakes, etc. were carried out in detail. In the present study we also tried to analyze the various components of the glaciers of Sikkim and Bhutan in an elevation wise scenario. As analyzing a huge dataset of glaciers without any sub-division or classification would not have done justice to the study. Therefore, glaciers were also categorized into 3 elevation classes i.e. <4000 m, 4000-5000 m, and >5000 m and analyzed. Parameters like the orientation of the glaciers, elevation both maximum and minimum, the maximum and minimum width of the glaciers and lakes, etc. provide additional information and were very useful for the part where Hazard Zonation of the moraine dammed lakes was discussed.

This enormous amount of data generated needs to be utilized, and thus the challenging task would be to use this data for specific tasks like, models for identifying potential sites for hydroelectricity generation, irrigation water needs and other industrial and domestic uses.

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