CHAPTER 1

Conceptual Framework

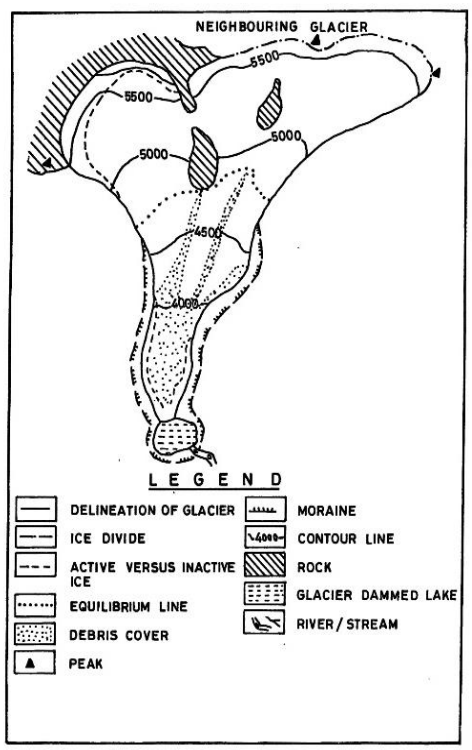
CONCEPTUAL FRAMEWORK

1.1:- General Description of Glacier

Glaciers are typically thought of as a mass of ice that moves down a slope steadily. Out of ice crystals, water and rock debris, ice is the most vital component of the glacier. Sugden and John (1976) classified glaciers into three groups based on their morphological characteristics which were bounded by topography viz. glacier, ice caps and ice sheets. When the underlying topography is completely covered by ice, ice sheet and ice cap develop and the glacier flow is unaffected by the geomorphology of the region.

Valley glaciers, cirque glaciers and ice fields, on the other hand, are glaciers whose movement is influenced by the structure of the valley and driven by the topography of the region. As a result, valley glaciers dominate the Himalayas. Valley glaciers may develop in an ice field or cirque built on the comparatively gradual slope of high mountainous terraces and glaciers therefore flow from ice fields to valleys.

Figure 1.1: Typical Diagram of Valley Glacier



Source: Anil V. Kulkarni (Unpublished PhD. Thesis, 1995)

The temperature of the ice mass can also be used to categorize glaciers. This is due to the fact that temperature has a significant impact on their morphological behaviours. This consideration splits glaciers into two types: temperate and cold. Since, Himalayan glaciers are temperate in nature, only those would be discussed here (Embleton and King, 1975).Temperate glaciers, on the other hand, are normally at the pressure melting point in their thickness, except for the highest few metres, which can become briefly colder in winter.In addition to this, melting also happens at the base of a temperate glacier due to the pressure melting point's reverse temperature gradient. Figure 1.1 depicts the usual outline of a valley glacier as well as other attributes such as the glacier boundary, equilibrium line, ice divide line, active and inactive ice, moraines and moraine-dammed lakes.

Present Distribution of Glaciers

Glacial ice, which includes glaciers, ice sheets and the ice fields of Greenland and Antarctica, occupies 10% of the Earth's land mass. Glaciers cover approximately 16 million square kilometers (5.8 million square miles). Glaciers contain about 69% of the world's fresh water. Glaciers occupied about 32% of the entire surface area at the peak of the last ice age which started around the 14th century and lasted to the mid-19th century. It is estimated that, if all land ice melts, global sea level will increase by around 70 metres (230 feet) (NSIDC, 2020). Outside of Antarctica (13.5 million square kilometers) and Greenland (2 million square kilometers), the Himalaya has the world's largest glacier belt, covering 15% of the land area (Ashish, et al., 2006) (Benn & Evans, 1998).

1.2:- Origin of the Research Problem

The direct source of knowledge on climate change is provided by the glaciers. (Nesje and Dahl, 2000). Mountain glaciers, in particular, are extremely susceptible to temperature and precipitation variations. They vary their mass balances, which impact their sizes, in response to minute variations in local climate (Oerlemans, 2005) and this can be used as a climate proxy. As a result, paleo-climatic assumptions are frequently relied on the extent of ancient mountain glaciers are determined by the location of their moraines (Refsnider et al., 2007). In the Himalayan Region, where the present glaciers are located, glacier lakes of all sizes and shapes were extensively spread. The fast accumulation of melt water in most of the moraine-dammed lakes in the basin has come from glacier retreat during the last decade. It has boosted their potential energy and decreased 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). After flight observations and field surveys in April 1992, Yamada and Sharma (1993) reported that, Imja Glacier Lake in the Khumbu district of Eastern Nepal to be the most dangerous in the region. This lake has a depth of 98.5metres with 28 million m^3 of water. Thus, this ice-cored moraine dammed lake is susceptible to outburst anytime. Similar incidences of dangerous lakes and GLOF'S are Nare GLOF (1977), the Dig Tsho GLOF (1985), the Tam Pokhari GLOF (1998) (Mool, 1995; Reynolds, 1998; Yamada, 1998, 2000; Mool and others, 2001; Bajracharya and others, 2007).

Available Resources and Literature Review

Earlier many methods have been devised for studying the glaciers and making their inventories. Glacier borders and associated elements were shown as rough outlines in the early seventeenth century. 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 first remark on the production of a systematic large scale map for glaciological purposes were made by Eduard Richter, the first chairman of the German and Austrian Alpine Club (Venediger Group, Alps). According to Brunner, 1987, Williams and Ferrigno (1988–2008) chronicled glacier mapping in a number of nations.

Raina and Srivastava (2008), on the other hand, presented a glacier inventory as well as historical records of glaciological investigations.in India including details on some glaciers. Since its founding in 1767, the Survey of India (SOI) has been India's primary agency for surveying the Himalayan mountain range. Many surveys have made significant contributions to glacier mapping in the Himalayas, including Colonel Godwin- Austen's plane-table surveys of the Mustakh range (Godwin-Austen, 1864), Conway's journey to the Hisper Glacier in 1892 (Conway, 1893) and Mason and Shipton's Shaksgam expedition (Mason, 1927a; Shipto et al., 1938) etc. All of these surveys made important contributions in a variety of areas, including mapping unexplored Himalayan valleys, correcting older maps and identifying improvements within glaciers based on previous maps etc. Furthermore, paving the way for the modern glacier inventory, the Survey of India released topographical maps of Himalayan glacier landscape at a scale of 1:50,000 in the 1960's based on aerial photographs and minimal fieldwork.

It was well established that earlier surveys employing terrain photogrammetry and plane-table necessitated a significant amount of time and human effort. In contrast, remote sensing techniques allow for faster glacier classification and if necessary, ground thruthing to get certain ground control points. The manual digitization of glacier boundaries on standard False Color Composites (FCC) of Landsat MSS and TM images began in Iceland and Austria by Williams (1986) and Hall et al., 1992 respectively, making them the first glacier inventory studies using remote sensing.

Given the fact that this method is very expensive, practically all glacier inventories in India that rely on satellite images are successfully accomplished by hand delineation. Beginning with Dhanju and Buch's (1989) inventory of the Parbati-Spiti Basin using TM-30 metre, Kulkarni and many other authors like Buch, Bahuguna etc. conducted several inventories between 1991 and 2010, and several other researchers conducted such glacier inventories in the Himalayan glacier (Table 1.1). FCC of coarse-resolution satellite data (e.g., MSS and LISS I) to high resolution data (e.g., LISS IV and PAN) and SOI topographic maps with scales ranging from 1:250,000 to 1:50,000 were used in these studies. Cartographic errors were also studied in few inventories based that were based on remote sensing and topographical maps. The Space Application Centre (SAC), Ahmedabad completed a 1:250,000 scale glacier inventory project for the entire Indian Himalayas in the early 1990's, which was a significant accomplishment (Bahuguna, 2008). GLIMS, ICIMOD, and GlobGlacier, in addition to the Himalayan Glacier Inventory by SAC, Ahmedabad, were databases that were referred for the present study.

Table 1.1: Details of Satellite Data Used in Glacier Mapping Studies of the Indian Himalayas				
Authors	**Location**	**Satellite data/map and spatial resolution/scale**	**Quantification of cartographic errors**	**Brief description**
Dhanju and Buch, 1989	Parbati – Spiti basin	Landsat TM-30 m	Not mentioned	For the manual demarcation of glaciers in this study, FCC bands 2, 3 and 4 were employed.
Kulkarni,1991	Himachal Himalayas	Landsat TM-30 m IRS LISS-II-36.5 m	Not mentioned	This study manually identified 125 glaciers using FCC (bands 2,3 and 4) satellite data.
Dobhal and Kumar, 1996	Himachal Himalayas	SOI topographical maps (1:250,000) Landsat TM-30 m	Not mentioned	With the exception of NE region of the Spiti basin, which was omitted owing to its geostrategic importance and restricted nature, the glaciers of the entire Himachal Himalayas were mapped.
Philip and Ravindran, 1998	Upper Bhagirathi basin	Landsat TM-30 m	Not mentioned	This study used Landsat TM to map the landforms of the Gangotri Glacier and found that FCC bands 4, 5 and 7 were appropriate for glacier mapping.
Kulkarni et al., 1999	Satluj basin	Landsat TM-30 m IRS LISS-II-36.5 m	Not mentioned	This study relied on SOI topographical maps for additional altitude data. The Himalayan Glacier Information System (HGIS) was created with the help of the dBase III application for this inventory.
Kulkarni and Suja, 2003	Baspa basin	IRS LISS III-23.5 m	Not mentioned	19 of the 30 glaciers in the Baspa basin were mapped in this research. Hanging glaciers, permanent snowfields, and rock glaciers were not included in this study.
Dobhal et al., 2004	Dokriani Glacier	SOI topographical glacial map (1:10,000)	Not mentioned	The Dokriani Glacier's ice volume change and rate of retreat were calculated in this study.

Kulkarni et al., 2005	Parbati basin	SOI topographical map (1:50,000) Landsat TM-30 m IRS LISS-III-23.5 m IRS PAN-5.8 m	Not mentioned	The Parbati Glacier was manually demarcated using multiple temporal satellite images in this study.
Krishna, 2005	Tista basin, Sikkim Himalayas	LISSI, LISSII and LISSIII satellite data of IRS	Not mentioned	The automated NDSI approach was employed in this study to map the snow cover.
Kulkarni et al., 2007	Himachal Himalayas	SOI topographical map (1:50,000) Landsat TM-30 m IRS LISS-III-23.5 m IRS LISS-IV-5 m	Not mentioned	The glaciers of the Chenab, Parbati and Baspa basins in Himachal Pradesh were manually mapped in this study.
Berthieret al., 2007	Spiti/Lahaul region	ASTER-15 m	±2 pixels (30 m)	The mass balance was estimated using manually drawn glacier boundaries in this study.
Source: Bhambri & Bolch, 2009				

GLIMS database includes the World Glacier Inventory (WGI/WGMS (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, the ICIMOD repository shares the GLIMS format, allowing it to be compatible with the GLIMS database for the future. The GLIMS data format was also used by the GlobGlacier database and their data is mostly already incorporated into the GLIMS database. Similarly, the GLIMS database includes the 2000 Chinese inventory and the current Chinese inventory is also 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).Glacial Lake Outburst Floods (GLOFs) 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. (Ding Yongjian and Liu 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 so 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.

1.3:- Significance and Justification of the Study

The gaps in these databases are as follows:-

GLIMS:

1) Little attention was placed on elevation histograms (but ICIMOD includes comprehensive histogram data from SRTM).
2) Glacier dammed lakes were primarily not organized according to drainage basins and sub-basins (but ICIMOD data are).

ICIMOD:

1) No delineation was made for accumulation/ablation areas.
2) Little attention was paid on dynamic parameters (changes).
3) Uncertainties of boundaries were not highlighted.

Hence, this study tries to cover the gap areas which are left in the earlier inventories.

1.4:- Objectives

The objectives of the present study are as follows:-

1) It aims at developing a methodology for inventorying glaciers.
2) Mapping the Glaciers and various glacier features.
3) Mapping the Moraine Dammed Lakes.
4) Finally Modelling a Hazard Zone for the Moraine Dammed Lakes.

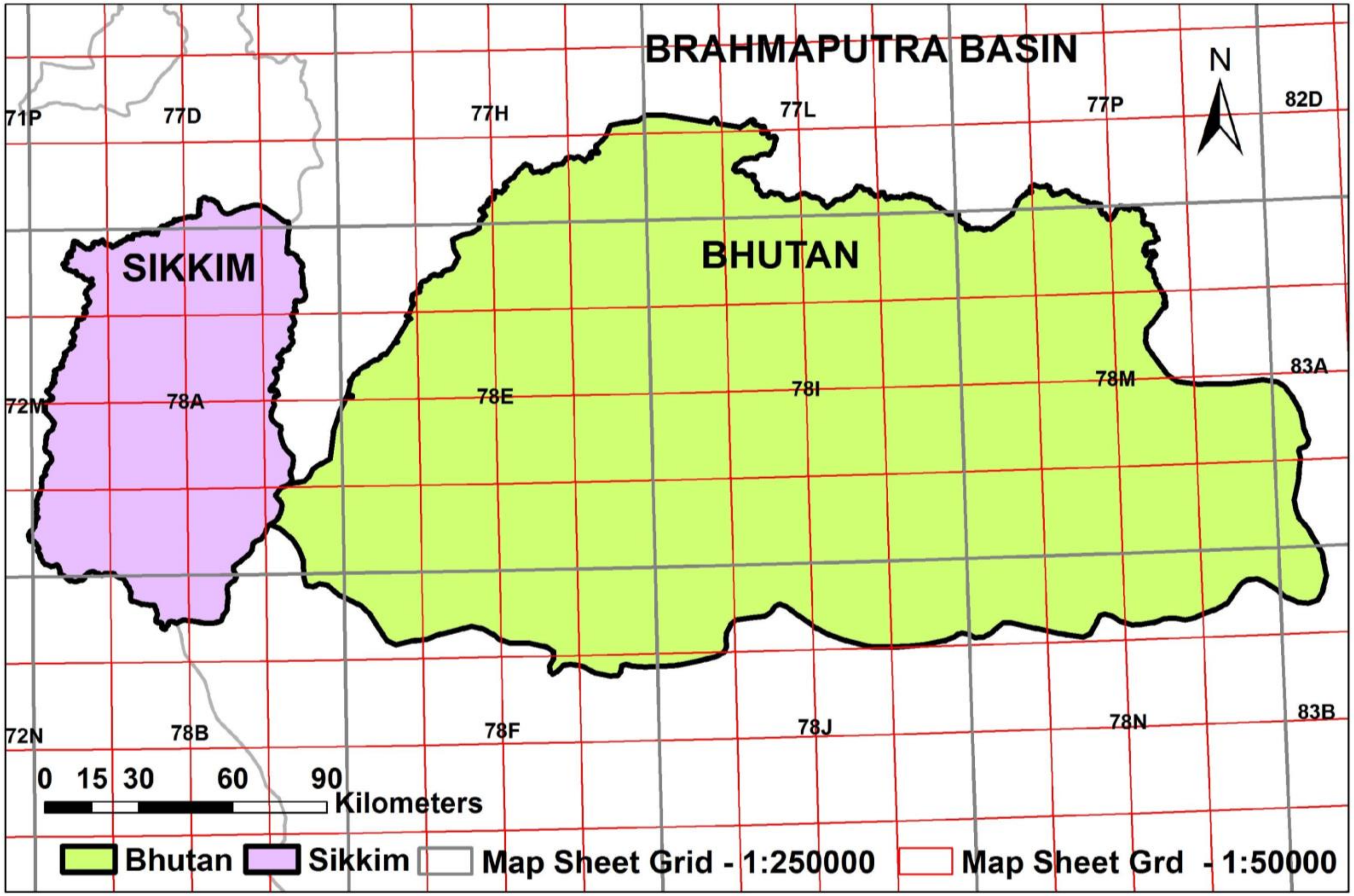
1.5:- Methodology for the generation of Glacier Inventory Maps and datasheets

Geocoded IRS LISS III data on a 1:50,000 scale were procured in digital format from July to the end of September (2004 – 2007), which are deemed as the ideal seasons for glacier inventory. Geocoded FCCs were acquired in digital format from the National Data Centre (NDC), National Remote Sensing Centre (NRSC), Hyderabad with the 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). Since the possibilities of obtaining high-quality cloudfree data with reduced snow cover were high with IRS AWiFS data having five-day repeatability thus, this data was also employed for glacier inventory. Satellite data from the years 2004 to 2007 have been used in general for the present inventory. Other satellite data, as well as data from the 2002-03 timeframe, were used for a few map sheets where 2004-07 IRS satellite data were not available. Furthermore, drainage maps from the Irrigation Atlas of India, Basin Boundary Maps from the Watershed Atlas of the All India Soil and Land Use Survey (AIS & LUS) and accessible Snow and Glacier maps (at 1:250,000) and various scales from the internet (GLIMS database, 2006) were incorporated for Sikkim (Kulkarni and Buch. 1991; Kulkarni et al., 1999 and 2005; Bahuguna et al., 2001). Collateral data for the state of Bhutan was retrieved from Survey of Bhutan (SOB) topographical maps at 1:50,000 scale (Figure 1.2), trekking routes, guide maps, political maps were referred for the delineation of political boundary and to define the study area. Drainage maps (Norbu, 2003) and Department of Survey and Land Records (RGOB, 1991) basin boundary maps were used to determine the basin boundaries and identify mountain ranges, as well as the network of streams and rivers flowing in the basin. For the identification of already mapped glacier data, available Snow and Glacier maps (at 1:250,000) (Kulkarni et al., 2005; Bahuguna et al., 2001,) were resorted to. In addition to these data, elevation data from DEM produced from SRTM data, road, hiking trail and guide maps, political and physiographic maps and published literature on Himalayan glaciers were used.

The glacier inventory map was generated using a soft copy of multi-temporal AWiFS and IRS LISS III satellite data and other supplementary data. According to previous field observations and satellite data analyses, the spectral reflectance of the accumulation zone is high in IRS LISS II and TM data bands 2, 3, and 4. Reflectance is higher in Bands 2 and 3 than in the natural environment but lower in B and 4 than in vegetation. These spectral characteristics can aid in distinguishing between glacial and non-glacial components (Dozier, 1984). Figure 1.3 is a flow chart that shows the broad framework for building a glacier inventory map, data sheet and digital data base (Sharma et al., 2006). In actuality, making a glacier inventory map requires constructing and merging major theme layers into a GIS.As shown in Table 1.2, the primary theme layers are divided into three categories: i) base detail ii) hydrological information and iii) glacier and de-glaciated valley features (Sharma et al., 2008).

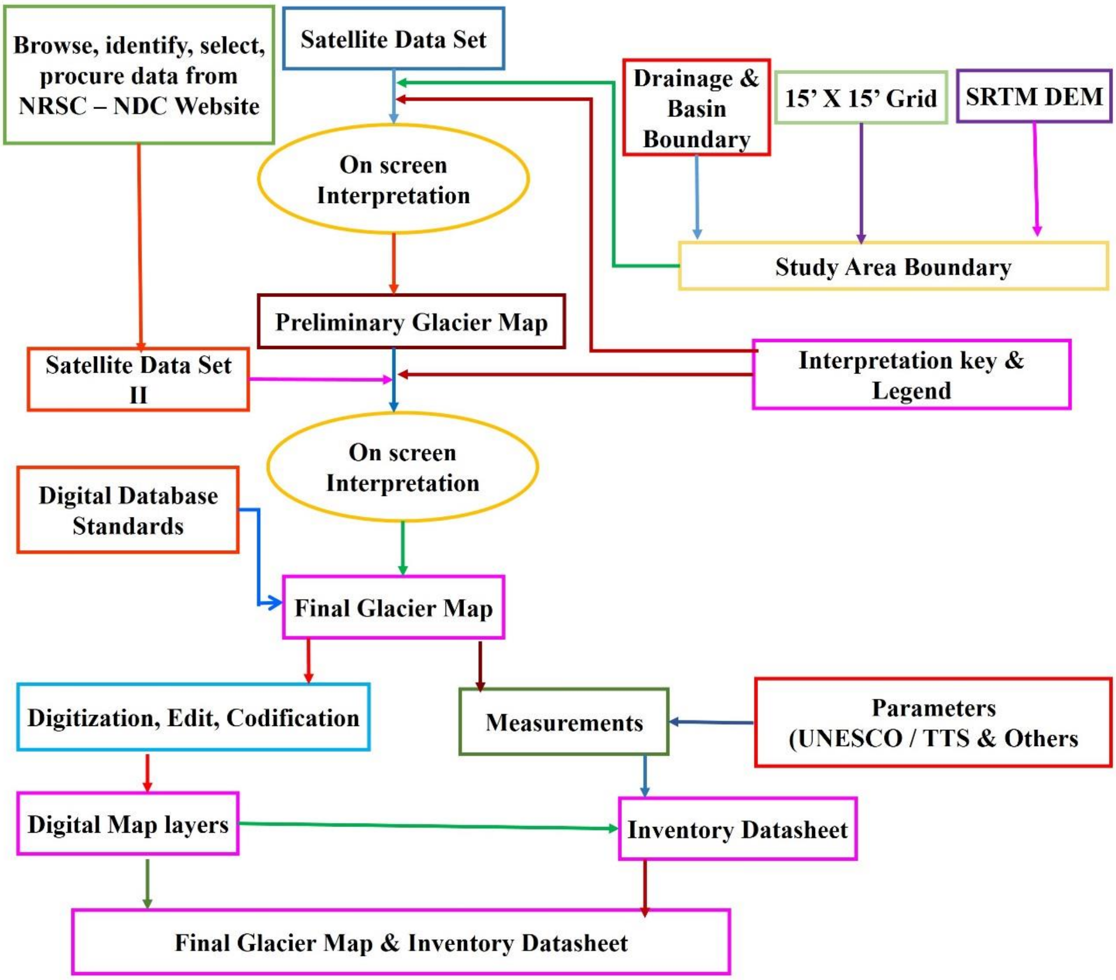
Table 1.2: Theme Layers for Glacier Inventory Map and Data Sheet Creation			
Theme	**Feature Type**	**Main Source**	**Remarks**
Base Map			
Graticule / grid	Point	SOI & SOB open series maps	5’ X 5’ latitude-longitude tic points
SOI & SOB	Polygon	SOI & SOB open series maps	15’X 15’ latitude-longitude grid and SOI & SOB reference numbers
Administrative Boundaries	Polygon	Published SOI & SOB and admin. maps	State/District, Taluka
Settlement	Point	Satellite data & Published maps	Location of habitation
Elevation	Grid/image	SRTM data	Image grid
Hydrology			
Drainage lines	Line	Satellite data	Streams with nomenclature
Drainage polygons	Polygon	Satellite data	Water bodies, river boundaries
Watershed boundaries	Polygon	AIS & LUS watershed maps, Satellite data	Watershed boundary and alpha numeric codes
Glacier			
Glacier Boundaries	Polygon	Satellite data	Accumulation, Ablation, Snow Covered Areas and Lakes
Snout location	Point	Satellite data	Position of Glacier Terminus
Snow/equilibrium Line	Line	Satellite data	Dividing line between accumulation / ablation
Ice divide	Line	Satellite data	Dividing line between glaciers
Valley Features			
De-glaciated Valley	Line	Satellite data	Extent of the de-glaciated valley
Moraine			
Moraine-P	Polygon	Satellite data	Includes moraines in de-glaciated valley and moraines / debris occurring on top of glaciers
Moraine-L	Line	Satellite data	Narrow moraine streaks
Source: Snow and Glaciers of the Himalayas, 2011 and Computed			

Figure 1.2: Study area - Sikkim and Bhutan divided into SOI & SOB Toposheets



Source: Computed

Figure 1.3: Broad Approach for Glacier Inventory Map and Data Sheet Preparation



Source: Snow and Glaciers of the Himalayas, 2011, Computed

To begin, preliminary digital maps corresponding to the base and hydrological themes were created using small scale auxiliary data (drainage, watershed, roads, settlements etc.). These early theme layers were refined and finalised using multi-temporal satellite data. The temporal changes (in database inventory parameter values) were verified for accuracy of prior database values in order to make reliable assessments of the changes.

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. Thus, Multi-temporal databases and their uncertainties, data gaps, and problems associated with each database were hence, analysed in due course of work. Glacier Analysis Comparison Experiment (standardized uncertainty assessment) where the magnitude of error would be assessed was thus conducted. For this purpose random checks of glaciers with the LANDSAT data ranging from 2000 to 2021 was done. Google maps was also used for the same purpose. If any corrections were needed, they were inserted into the final glacier inventory maps. The glacier data sheet was created as a result of measurements made on the glacier inventory map. Furthermore, the Glacial Lakes were also mapped and studied in this research due to which the GLOF's were also be included in the inventory studies.

Preparation of Theme Layers

As base maps and hydrological theme layers, Irrigation Atlases, Watershed Atlases, Small and Large scale maps such as political/physical maps have been employed. Administrative boundaries, transportation, settlement locations, irrigation, watersheds and other elements were specified on these maps. Following that, the maps were scanned as raster images and registered/projected with satellite data using standard control features. The base information was extracted on different vector layers using these scanned images in the background. The subsequent subsections go through the information content of each of the primary theme layers as well as the process for preparing them:

Base Map Layers

The administrative boundary layer, settlement locations and elevation information (DEM) layer make up the three categories of layers that make up the base map.

Administrative Boundary Layer

Political maps (or SOI & SOB open series maps) are used to obtain significant administrative boundaries like that of the national level. These borders were defined, delineated, codified and maintained as distinct layers with corresponding look-up tables in a digital data base (Table 1.3 and Table 1.4). The country codes given by UNESCO/TTS/Muller were adopted.

Table 1.3: Structure of Table: COUNTRY.LUT

Field Name	Field Type	Key Field- Y/N
COUNTRY-CODE	2,2,C	Y
COUNTRY-NAME	10,10,C	N

Source: Snow and Glaciers of the Himalayas, 2011

Table 1.4: Attribute Tables for Country: COUNTRY.LUT	
COUNTRY-CODE	**COUNTRY-NAME**
IN	India
BH	Bhutan
Source: Snow and Glaciers of the Himalayas, 2011	

These administrative layers were not generated with the aid of satellite data. These were, however, key reference layers for understanding glacier distribution across political boundaries. These layers were obtained directly from Survey of India and Survey of Bhutan (SOI and SOB) as open series digital maps. In this analysis, the administrative maps were explicitly integrated into the data base.

Settlement Location

The lower reaches of the basins are populated and the presence of small settlements are typical. The boundaries of such villages/towns were first defined using published maps and saved as a polygon (SETTLEA) layer or habitation mask. The settlement extent (polygon) of villages and towns is modified using multi-date satellite data and the subsequent codification was conducted using the SETTLEA.LUT look-up table (Table 1.5 and Table 1.6). The settlement location point (SETTLEP) was marked as the centeroid of the delineated polygon for settlement and all related information was added to this point in the look-up table SETTLEP.LUT (Table 1.7). Each village's SETTLEP code corresponds to the codes mentioned in Census (2001).

Table 1.5: Structure of Table: SETTLEMENT.LUT			
Field Name	**Field Type**	**Key Field- Y/N**	**Remarks**
SETA - CODE	4,4,C	Y	Feature Code
SET- TYPE	30,30,C	N	Code Description
Source: Snow and Glaciers of the Himalayas, 2011; NRIS			

Table 1.6: Attribute Table for Settlement (Polygons): SETTLEA.LUT	
SETA - CODE	**SET- TYPE**
01	Towns/ Cities (Urban)
02	Villages (Rural)
Source: Snow and Glaciers of the Himalayas, 2011; NRIS	

Table 1.7: Attribute Table for Settlements (Points): SETTLEP.LUT			
Field Name	**Field Type**	**Key Field- Y/N**	**Remarks**
SCODE	8,8, C	Y	
LOCATION	25,25,C	N	Village Name
SCODE is the system link CODE			
SCODE	V -TYPE		
00009000	Village		
00009002	Town		
Source: Snow and Glaciers of the Himalayas, 2011; Anonymous, 2000			

Elevation Information Layer (DEM)

The elevation information was retrieved using a DEM generated using the Shuttle Radar Terrain Mapping (SRTM) Mission with a vertical resolution of 30 metre. The DEM is overlaid with the point location layer and substantial elevation measurements needed for the data sheet were extracted.

Hydrology

The subsequent hydrology layer includes information on minor and major drainage, water sources and watersheds, as well as their corresponding identification numbers and names. The preliminary drainage line and waterbodies layers were produced using the published small scale Irrigation Atlas of India as input. The tentative watershed (Basin/Sub-basin) layer was created using the Watershed Atlas of India as reference. The drainage layer was made up of two layers: a drainage line layer (DRAINL) and a drainage polygon layer (DRAINP).

Drainage Polygon Layer

At this scale, this layer contained details of the main streams and water bodies, which have been represented as polygons. Through proper codification, the dry and wet areas of the drainage were defined and delineated. The sand area, which is periodically flooded due to snow melt, should also be properly defined and mapped. The supra-glacial lakes and moraine dammed lakes were delineated and categorized accordingly (DRAINP.LUT) (Table 1.8 and Table 1.9). The names of major bodies of water and rivers were derived from published maps and stored in the look-up table's associated database.

The preliminary drainage line and polygon layers, which were created with small scale maps as input, were both modified using multi-date satellite data. The final drainage layers incorporated all changes in stream/river courses as well as the presence of new water bodies.

Table 1.8: Structure of the Table DRAINP.LUT

Field Name	Field Type	Key Field- Y/N	Remarks
DRNP-CODE	2,2, C	Y	Feature Code
DISCR	30,30,C	N	Code Description

Source: Snow and Glaciers of the Himalayas, 2011**;** Anonymous,2000

Table 1.9: Attribute Table for Water Body Polygons: DRAINP.LUT

DRNL-CODE	DISCR
01	River
03	Lakes/ Ponds
10	Supra-glacial lake
11	Moraine dammed lake

Source: Snow and Glaciers of the Himalayas, 2011**;** Anonymous,2000

Drainage Line Layer

The drainage line layer was prepared to represent all the streams arising from the snow and glacier feed area and which was represented only as single line due to mapping scale (DRAINL.LUT) as given in Table 1.10.

Table 1.10: Structure of the Table DRAINL.LUT			
Field Name	**Field Type**	**Key Field- Y/N**	**Remarks**
DRNL-CODE	2,2, C	Y	Feature Code
DISCR	30,30,C	N	Code Description
Source: Snow and Glaciers of the Himalayas, 2011**;** Anonymous,2000			

Watershed (Basin / Sub-basin) Boundary Layer

The hierarchical (preliminary) watershed boundary details were obtained from the Watershed Atlas small scale watershed maps. The preliminary map's delineated borders were updated using multi-date satellite data. To prepare the final watershed (Basin / Sub-basin) map layer, the ridges, ice divide and stream/river features seen on the image were carefully interpreted and refined at 1:50,000 scale.

Glacier

Mountain and valley glaciers are the most common types of glaciers in the Himalayas. Before starting the mapping, the available archive information on glaciers in the form of glacier maps / Atlas on the Himalayan Glacier Inventory at 1:250,000 scale (Kulkarni and Buch, 1991) were consulted this helped in understanding the past glacier occurrences and distribution. The requisite glacier morphological features were mapped using multi-date satellite data. These morphological features were processed separately as line, point and polygon layers for the convenience of generating statistics from digital layers. The glacier inventory map was produced in two stages. First, a preliminary glacier inventory map was created using the first set of satellite data and all glacier features (Figure 1.4) were identified and mapped. Basic glacier inventory map was prepared by mapping the complex features such as the snow line, permanent snow covered area, moraine extent and so on were updated and new glacier features, if any, were appended based on subsequent year satellite data.

The glacier characteristics mapped were the permanent (for two or more glacial inventory seasons) snow covered regions/snow fields, the boundary of smaller glacierets, the Glacier boundary for accumulation and ablation area and the transient snow line dividing the two areas.

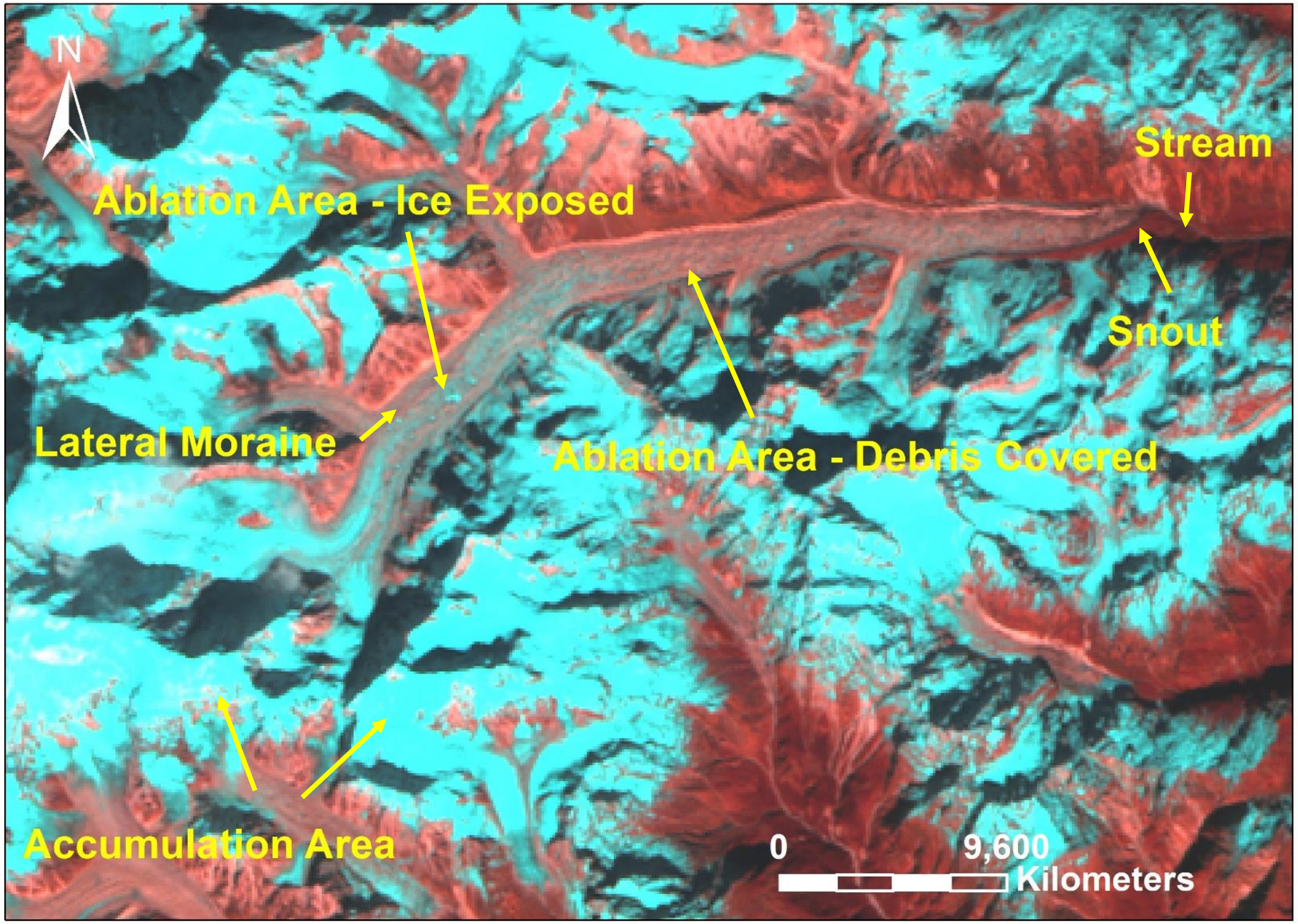
The ice divide line at the glacier's margin, as well as other features like the cirque, horn, glacial outwash plain zones, glacier terminus / snout, and so on, were all delineated.

The ablation zone was further classified as ice-exposed and debris-covered. The characteristics of the lateral and medial moraine associated with ablation zones were also defined. If there were any supra-glacier lakes, these were also delineated. The length of the de-glaciated valley, as well as the associated moraines and moraine dammed lake features, were delineated. These properties were saved in GIS as point, line, and polygon layers.

Glacier Features Layers

The extent of perennially snow-covered areas, the glacieret, the glacier accumulation and ablation area and other glacier-related features were delineated as polygon features (GLACIER) and appropriately codified using multi-date satellite data (GLACIER.LUT). The ice divide line at the margins of two or more glaciers, as well as the temporary snow line that divides the accumulation and ablation zones, were defined and delineated as line features in a separate cover. The glacier's center line, which divides it into two equal halves and runs along its full length/longitudinal axis, was delineated and saved as a line feature (GLACIERL). In a separate cover, the glacier terminus or snout was delineated as a point eature (GLACIERP). Tables 1.11, 1.12, 1.13, 1.14, 1.15 and 1.16 demonstrate the associated look-up tables for the glacier poly, line and point features as GLACIER.LUT, GLACIERL.LUT and GLACIERP.LUT, respectively, as well as the corresponding structure for each of these.

Figure 1.4: Glacier Features as seen on AWiFS FCC (September, 2015)



Source: Computed

Table 1.11: Attribute Code Table for Glacier Polygon Layer: GLACIER.LUT			
GL-Code	**Discr-L1**	**Discr-L2**	**Discr-L3**
01-00-00	Glacier		
01-01-00		Accumulation area	
01-02-00		Ablation area	
01-02-01			Ablation area: debris cover
01-02-02			Ablation area: exposed
01-03-00		Moraine	
01-03-01			Terminal moraine
01-03-02			Medial moraine
01-03-03			Lateral moraine
01-04-00		Supra glacier lakes	
02-00-00	De glaciated valley		
02-01-00		Moraine	
02-01-01			Terminal moraine
02-01-02			Lateral moraine
02-02-00		Outwash plain	
02-03-00		Moraine dammed lake	
03-00-00	Glacieret & Snow field		
88-88-88	Non glaciated area		
Source: Snow and Glaciers of the Himalayas, 2011			

Table 1.12: Structure of the Table GLACIER.LUT			
Field Name	**Field Type**	**Key Field- Y/N**	**Remarks**
GL-Code	6, 6, C	Y	Feature Code
GLAC_ID	15,15,C	Y	Glacier identification number
Discr-L1	50,50,C	N	Glacier Unit at very small scale
Discr-L2	50,50,C	N	Glacier Unit at large (1:50k) scale
Discr-L3	50,50,C	N	Glacier Unit at large (1:50k) scale with next level of (hierarchy) details
Source: Snow and Glaciers of the Himalayas, 2011			

Table 1.13: Attribute Code Table for Glacier Line Layer: GLACIERL.LUT	
GLL - Code	**Discr-L1**
01	Ice divide line
02	Lateral Moraine glaciated area (trace)
03	Median Moraine in glaciated area (trace)
04	Terminal Moraine in glaciated area (trace)
05	Lateral Moraine in de-glaciated area (trace)
06	Terminal Moraine in de-glaciated area (trace)
07	Transient snow line
08	Centre line of total glacier (max. length)
09	Centre line of glacier (2) smallest (min. length)
10	Centre line of total de-glaciated valley (max. length)
11	Centre line of exposed glacier (max. length-exposed)
12	Centre line of ablation area (max. length)
13	Mean width line for ablation area – maximum length
14	Mean width line for ablation area – minimum length
Source: Snow and Glaciers of the Himalayas, 2011	

Table 1.14: Structure of the Table GLACIERL.LUT			
Field Name	**Field Type**	**Key Field-Y/N**	**Remarks**
GL-Code	2, 2, C	Y	Feature Code
GLAC_ID	15,15,C	Y	Glacier identification number
Discr	50,50,C	N	Glacier Line Feature at large (1:50k)
Source: Snow and Glaciers of the Himalayas, 2011			

Table 1.15: Attribute Code Table for Glacier Point Layer: GLACIERP.LUT	
GLP - Code	**DESCRIPTION**
01	Terminus / snout
02	Glacier coordinate point
03	Supra-glacial lake coordinate point
04	De-glaciated valley coordinate point
05	Moraine dam lake coordinate point
06	Snowline coordinate point
Source: Snow and Glaciers of the Himalayas, 2011	

Table 1.16: Structure of the Table - GLACIERP.LUT			
Field Name	**Field Type**	**Key Field- Y/N**	**Remarks**
GL-Code	2, 2, C	Y	Feature Code
GLAC_ID	15,15,C	Y	Glacier identification number
Discr	50,50,C	N	Glacier co-ordinate point location
Source: Snow and Glaciers of the Himalayas, 2011			

The glacier locations as represented by the latitude/longitude and coordinate system were required by the TTS format. Similarly, for tabular representation and future reference, different point positions representing the coordinate point for de-glaciated valley, supra-glacier lake, snout, moraine dam lake, and so on were needed. For this, the GLACIERP layer with point position (coordinates in latitude/longitude) was established.

De-glaciated Valley Feature

The health of the glacier is determined by the de-glaciated valley and its related features. The glacier's retreat pattern is influenced by the valley's size and the type of moraines deposits. The extent of the de-glaciated valley features is identified and delineated using multi-date satellite data. Among the de-glaciated valley and related landforms mapped are glacial valley moraines such as the terminal, medial, and lateral moraines, outwash plains, and moraine dammed lakes. Depending on their width at the mapping scale, moraines may appear as both polygon and line features. The information is thus saved in the GLACIER (polygon vector) layer. The de-glaciated valley line (GLACIERL) layer keeps track of some of the lateral and terminal moraines which are only delineated as lines.

Elevation data, especially the highest and lowest elevations of glaciers, de glaciated valleys, supra-glacial and moraine dam lakes, is important because it was included in TTS format. Many of the coordinates of these elevation points, as well as their elevation values, were stored in a point layer (ELEVP). Tables 1.17 and 1.18 display the ELEVP's attribute table as well as its composition. This layer was intersected with the DEM layer generated using SRTM data to extract elevation information for these positions.

Table 1.17: Attribute Code Table for Elevation Point Layer: ELEVP.LUT

ELEV - Code	DESCRIPTION
01	Highest glacier elevation point
02	Lowest glacier elevation point (same as snout location)
03	Lowest supra-glacial lake elevation point
04	Lowest moraine dam lake elevation point
05	Snowline elevation point / high elevation ablation area / low elevation of accumulation area
06	Lowest De-glaciated valley elevation point

Source: Snow and Glaciers of the Himalayas, 2011

Table 1.18: Structure of the Table - ELEVP.LUT

Field Name	Field Type	Key Field- Y/N	Remarks
ELEV-CODE	2, 2, C	Y	Feature Code
GLAC_ID	15,15,C	Y	Glacier identification number
ELEV-VAL	5,5,I	N	Glacier elevation value in metres
DISCR	50,50,C	N	Various glacier elevation point

Source: Snow and Glaciers of the Himalayas, 2011

Steps Involved in the Preparation of the Glacier Inventory Map and Data Sheet

With around 102 (15' x 15' grid) map sheets of 1:50,000 scale, a spatial structure for the two Eastern Himalayan basins under study was developed (Figure 1.2). The database was characterized in terms of (a) the WGS84/UTM coordinate and projection framework. (b) Tic marks at 5 minute intervals at longitude-latitude intersections, (c) Coordinate units were in metres (Sharma et al., 2008).

The mosaicked / edge aligned sheet-by-sheet thematic layers were then combined with the database. Some spatial data attributes, such as glacier maximal length/width, were generated primarily to provide direct inputs to the spatial data format not be used in final cartographic outputs as a detailed database was to be generated later. Non-spatial data such as glacier name, identification number, classification, elevation and so on were stored in a dat file (GLACERI.DAT) and connected to spatial data through the key field (GLAC ID). The database architecture makes it simple to extract aspatial information from spatial data.

1.6:- Database Organization

The database's structure recognizes the fact that the system must facilitate information retrieval in terms of spatial units. This information would be used to analyze various components of Glacier Inventory at a later stage. The database was organized into strata that comprised hydrological units, administrative boundaries (States) and toposheets/ map sheets. Since the input data was in the form of maps, each hydrological or administrative unit usually includes more than one map sheet, partially or entirely which was organized in ArcGIS environment.

1.7:- Generation of Final Glacier Inventory Map - Step wise Glacier Delineation

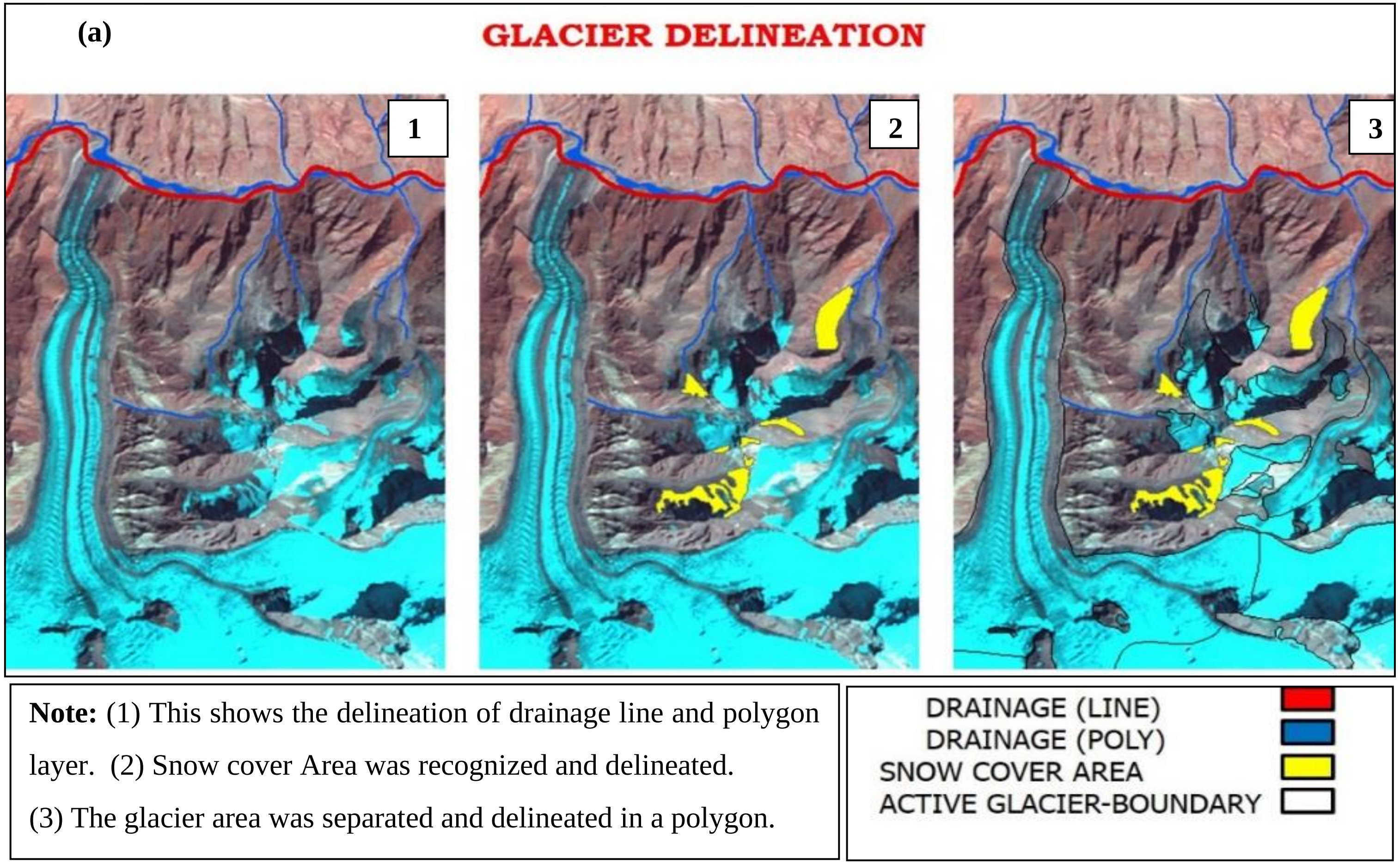
Accurate glacier delineation is only achievable with proper understanding of satellite imagery. Glacier may only be distinguished by a thorough understanding of elements like as tone, texture and other associative features, amongst many others. As a result, in this section, we attempt to comprehend the techniques and methods of glacier identification and delineation.

Important Conditions for Glacier Delineation

Certain parameters must be met in order to properly delineate glaciers. These may be summarized in a few lines. Due of the evident textural changes, optical bands AWiFS Band 2 (green - 0.52 – 0.59 m) and Band 3 (red - 0.62 – 0.68 m) aided in distinguishing the Glacier boundaries. Snout of the glacier was identified with the help of the shadow of the glacier cave, its association with stream and glacier lakes. The debris cover was mapped with the help of its association and rough texture seen on the satellite data. The snow line, which acts as a transition line between accumulation and ablation zones, was mapped using band combinations 2, 3 and5, with moraines taken into account. The snow line was mapped using two years of multi-date data, as it shifts depending on the quantity of snowfall in the region. The glacial moraines, on the other hand, were demarcated by the tone of the glacier, the rough texture, the elongated patterns of the moraines and their placement on the sides, centre or the terminus of the glacier. The final band SWIR (1.55 – 1.70μm) was used to differentiate between snow and cloud cover in the satellite data. Since snow absorbs light and clouds reflect it, it is easy to distinguish between the two in this photograph.

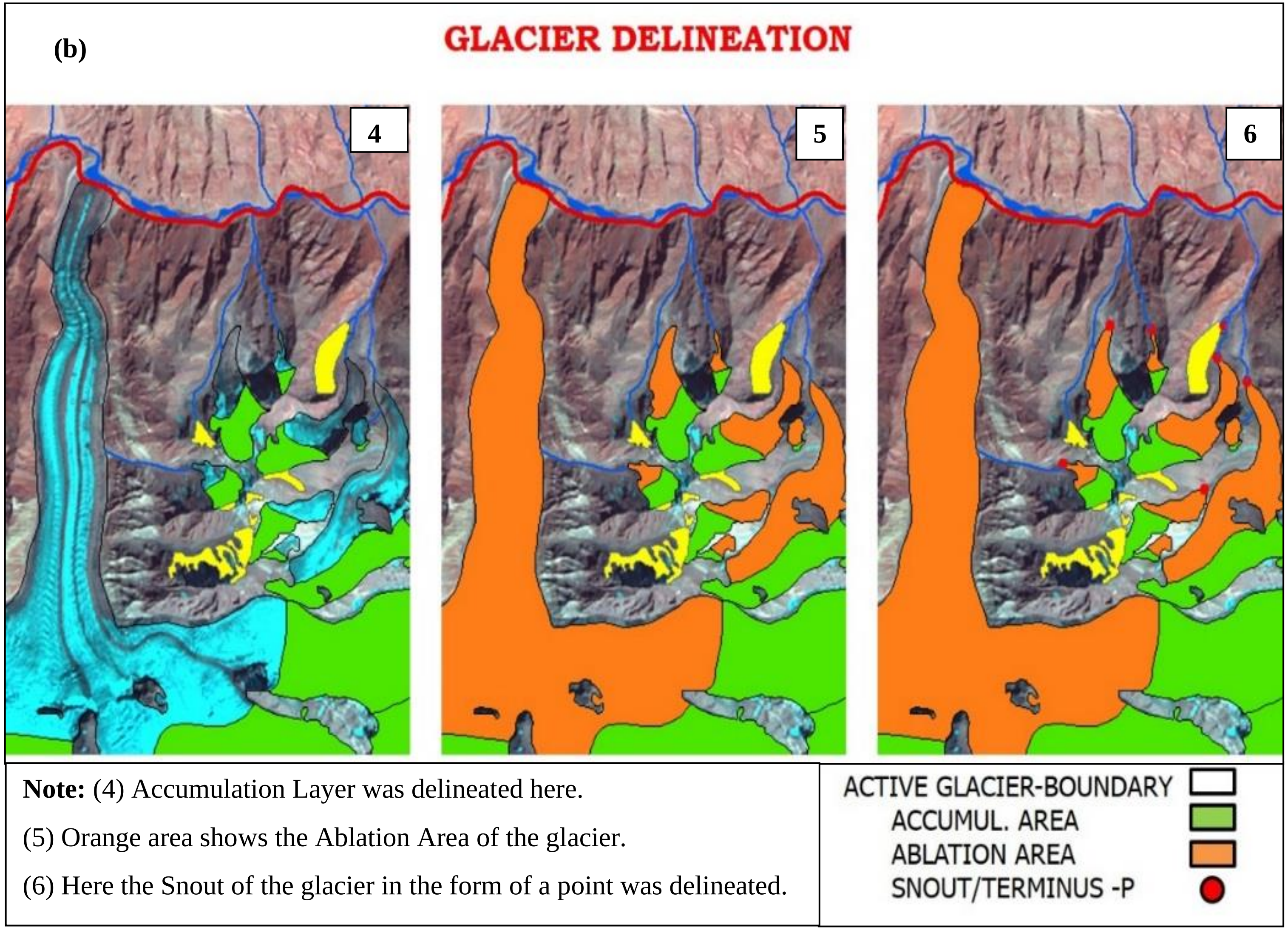
To build the final glacier inventory map, the previously identified layers of data were meticulously merged in a digital database in a GIS environment. Cartographic maps are generated by superimposing multiple layers in GIS and employing proper symbology for each of the elements associated with the base map, hydrology, and glacier feature layers (Figure 1.5). Some of the mapped layers were selectively excluded from the final map composition as they were only used to estimate dimensions.

Figure 1.5: Step wise Glacier Delineation



Note: (1) This shows the delineation of drainage line and polygon layer. (2) Snow cover Area was recognized and delineated. (3) The glacier area was separated and delineated in a polygon.

(b)

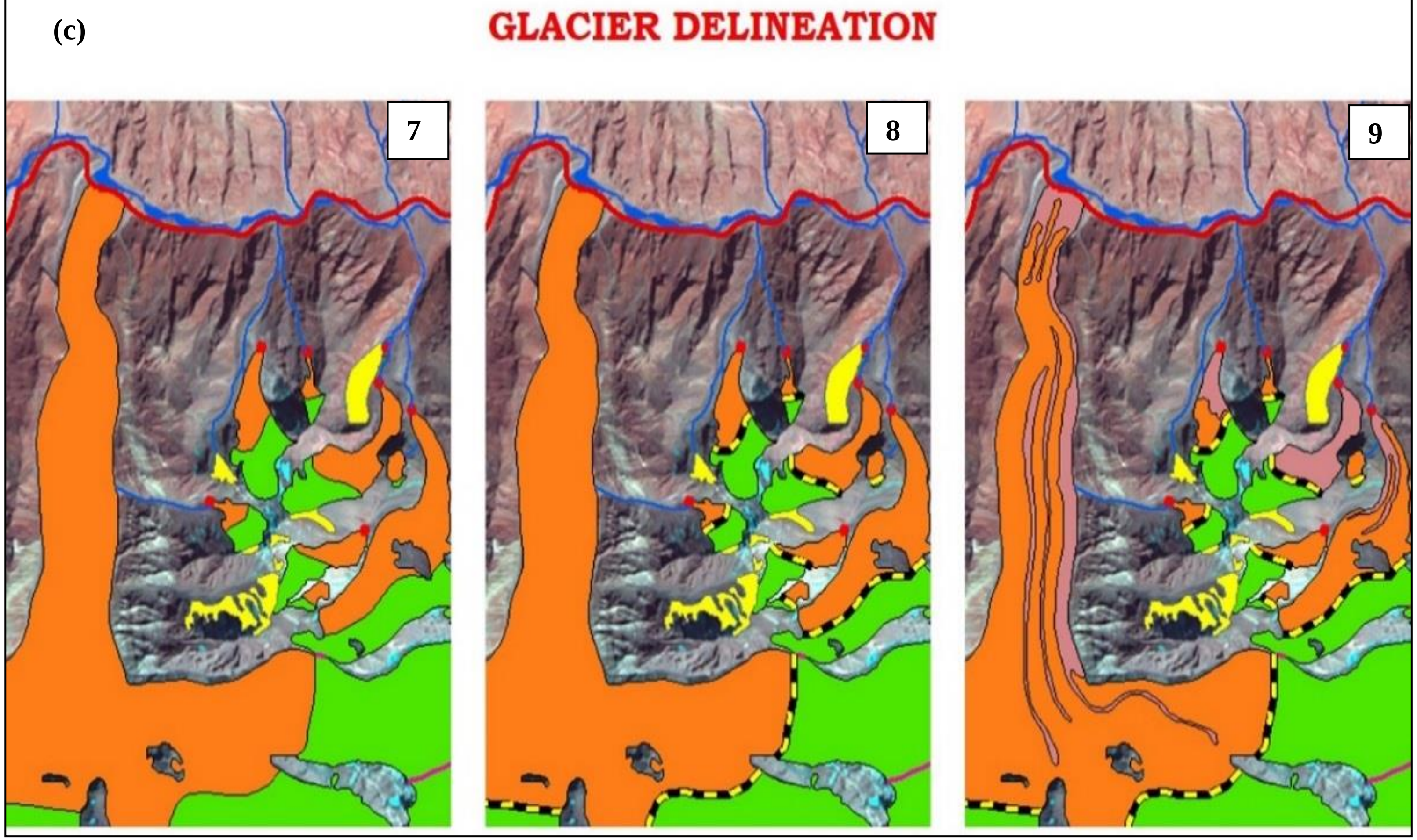


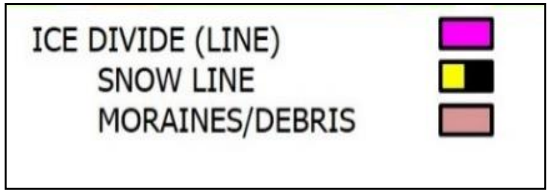
Note: (4) Accumulation Layer was delineated here.

(5) Orange area shows the Ablation Area of the glacier.

(6) Here the Snout of the glacier in the form of a point was delineated.

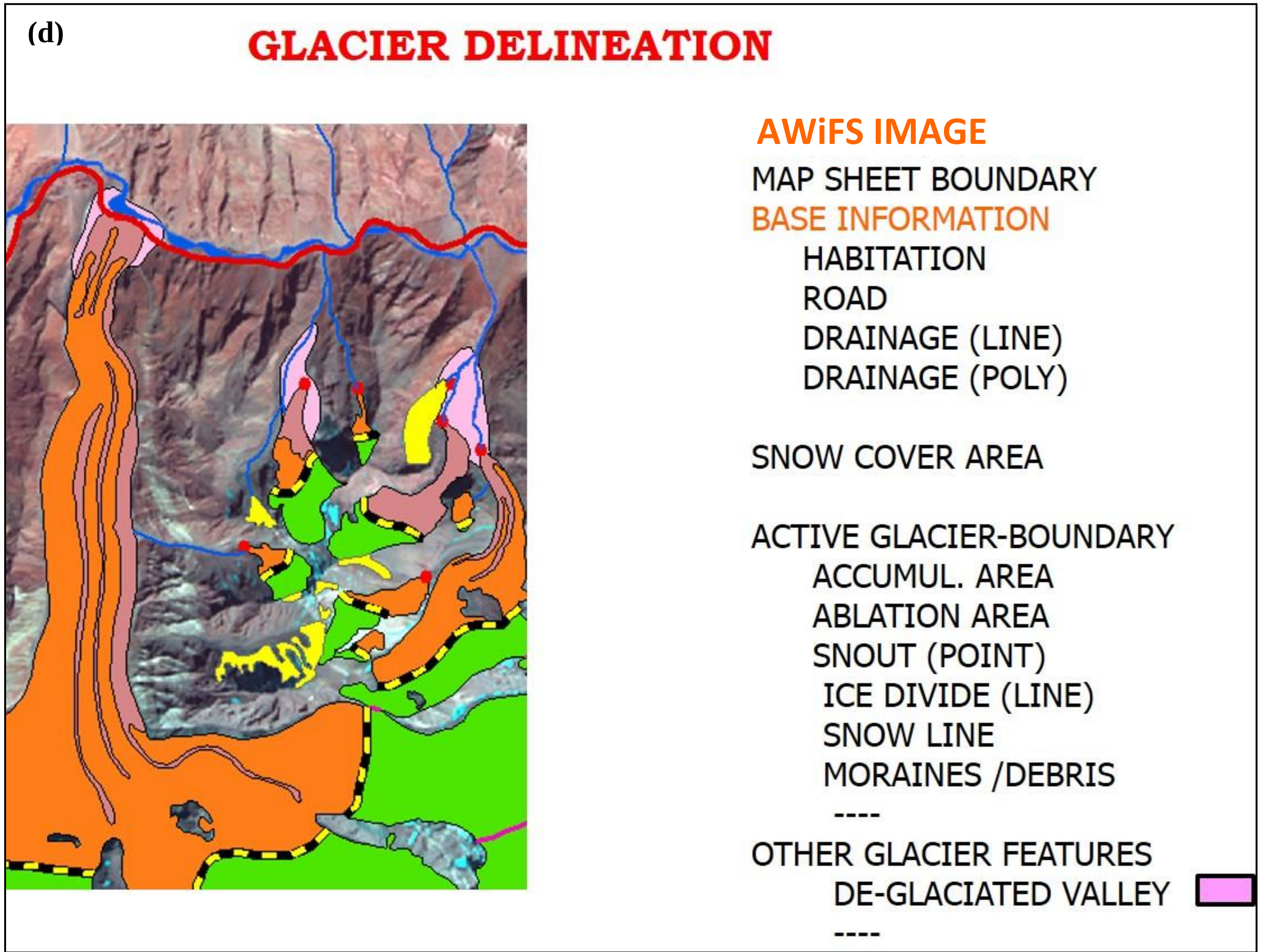
(c)





Note: (7) Ice Divide Line delineation can be seen in the accumulation zone (8) Snow Line separating the ablation and accumulation zones was made.

(9) Medial and Lateral Moraines in ablation area were demarcated.



Note: This figure shows how a glacier looks in a vectorized format. All mapped glacier features are seen here.

Quality Assessment

Four Stages of Quality Check & Quality Assessment: -

- Satellite data browed, ordered & registered
- Individual Vector Layers checked.
- All vector layers mosaiced.
- Check at the Database & Datasheet level.

1.8:- Steps Involved in the Calculation of AAR – Accumulation Area Ratio

Besides preparing the glacier inventory data, Accumulation Area Ratio (AAR), calculation and estimations of glacier thickness and ice reserves have been also attempted. AAR is the ratio of the accumulation area to the glacier's total area while volume of ice is the relation between mean ice thickness (H) and glacier area (F) established from the ground study of some glaciers in Himalayas (Liu and Ding, 1986; Shi et al., 2008).

$$H = -11.32 + 53.21\ F^{0.3}$$

Where: - H = Volume of Ice

F = Total Glacier Area

This formula was used to estimate the mean ice thickness of the Sikkim and Bhutan sub-basin and the result is expressed in Cubic Kilometer (km^3).

Resume

The first chapter covers the fundamentals of research. These include the "Origin of the Research Problem," as well as the "Research Framework," that encompasses the "Available Resources and Literature Review." This chapter also discusses about the "Significance" of the study and "Justifies" the research endeavour and its "Objectives." The broad "Methodology" that explains the flow of the study and "Database Organization" are extensively discussed. The "Study Area" will be covered in the next chapter.