CHAPTER 3

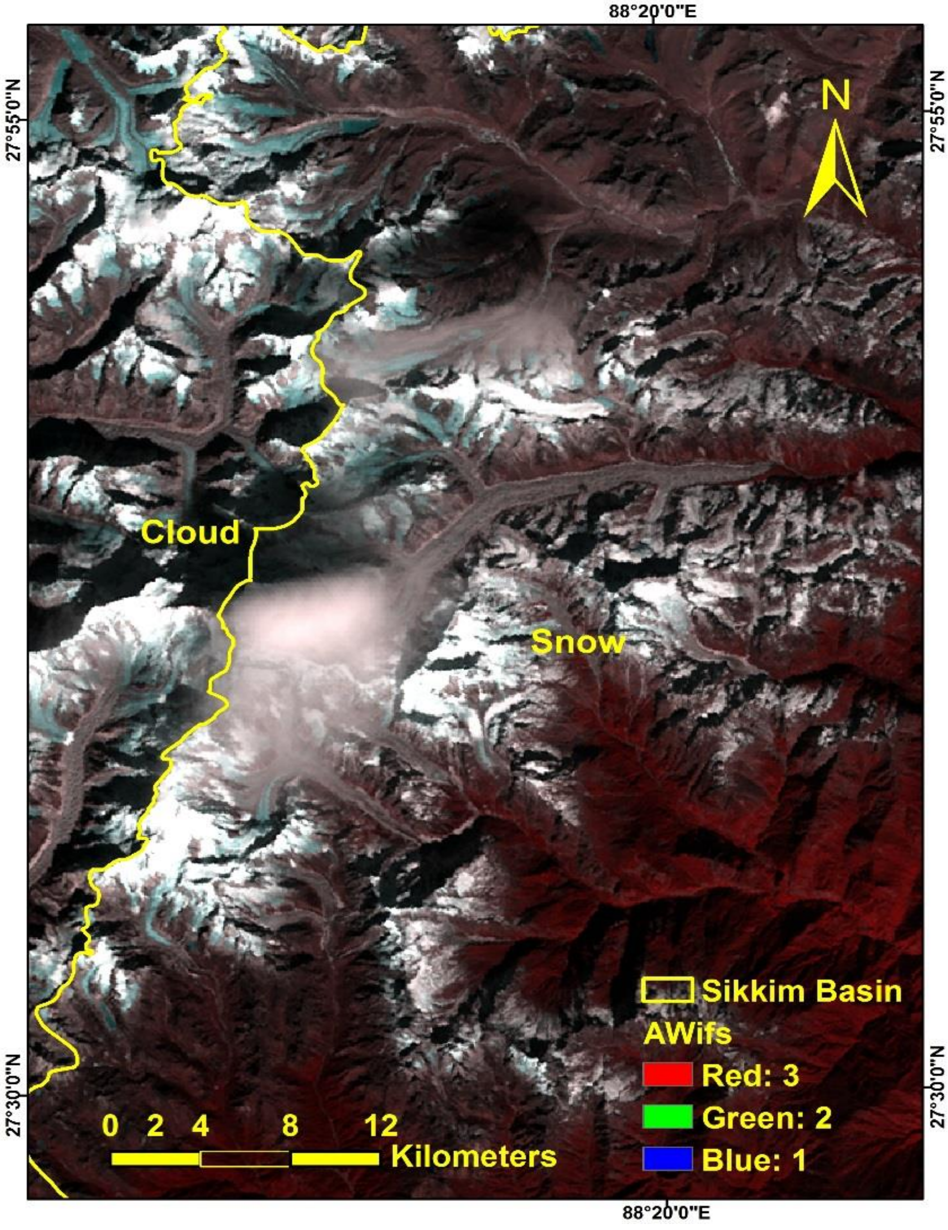
Glacier Inventory

GLACIER INVENTORY

3.1:- Glacier Inventory

As discussed in the previous chapters, the various satellite sensors have different bands. Out of these bands, the glacial characteristics are easily identifiable in the standard FCC (False Color Composite) of Resoursesat-1. FCC, that is, standard combination of wavelength bands 2 (0.52–0.59 µm), 3 (0.62–0.68 µm) and 4 (0.77–0.86 µm) as well as the

Figure 3.1: Snow and Cloud Ambiquity - Sikkim (78A)

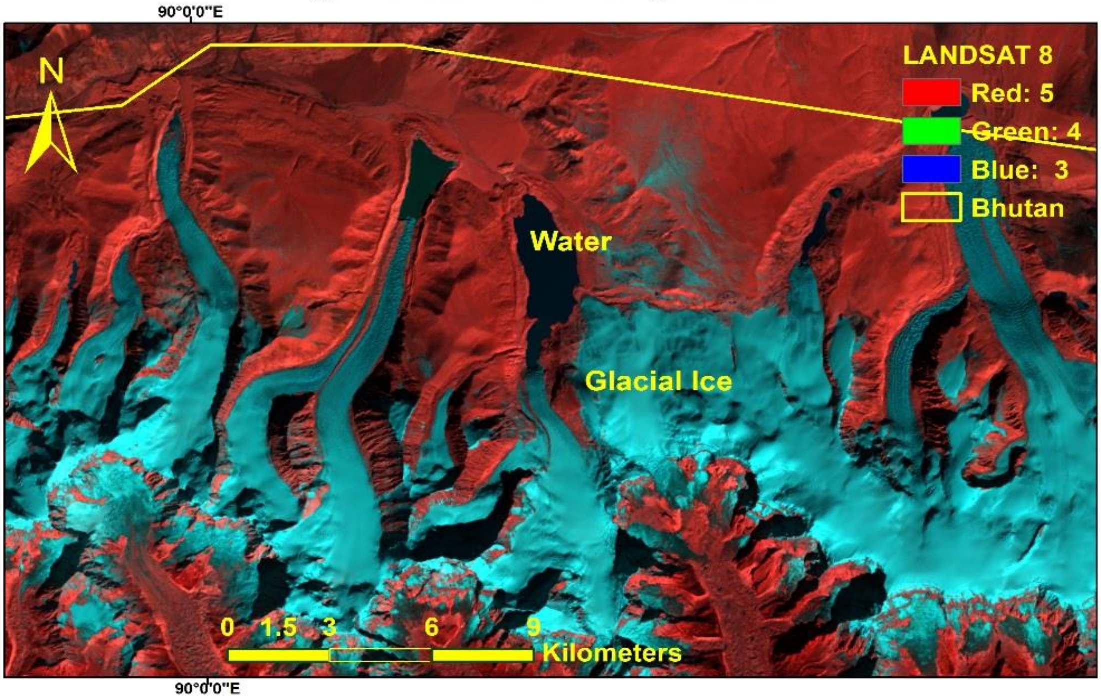


Source: Computed

shortwave infrared (SWIR) band 5 (1.55–1.70 µm) were used. The standard false colour composite was used to create blue, green and red colors for bands 2, 3 and 4, respectively (Kulkarni, 2001). The glacier boundary is evident in FCCs with a band combination of 2, 3 and 4/5, which enables the identification of textural variation as well as the presence of minor vegetation, especially grasses, scrubs, etc. For mapping different glacier features such as ablation area, accumulation area, glacier boundary, equilibrium line and moraine-dammed lakes, this combination is proven to be useful. Image characteristics of the individual features were also addressed in Section 3.2

Owing to the presence of cloud cover, mapping of the accumulation region is often difficult. This is because snow and cloud image characteristics are analogous (Figure 3.1). Therefore, in order to prevent ambiguity between snow and cloud, band 5 of the Landsat TM sensor (1.55-1.75 µm) is helpful. Using bands 3, 4 and 5, a composite was prepared by allocating blue, green and red colors to them, respectively. The contrast between cloud and snow is probable in this combination, as seen in Figure 3.2. The snow cover appears blue in this image, while the vegetated regions appear in yellow and green tones. The distinction of the ablation areas from the rocky surrounding areas, though, becomes a challenge. This band combination is then only used to accurately define the accumulation region, which becomes challenging because of the presence of cloud cover.

Figure 3.2: LANDSAT Image - Bhutan



Source: Computed

3.2:- Identification of the Glacier Features through Satellite Imagery

To map the Glaciers through the Satellite Images, a knowledge of how glaciers look on the remotely sensed data is must.

Polygon Features

Calculation of the area for various features like the Glacier Boundary, Ablation Area, Accumulation Area, Lakes etc. is required for the Inventory. Hence, these features are delineated as Polygon Features.

Glacier Boundary

The delineation of the glacier boundaries is actually the distinction between the non-glaciated area and the glaciated area. This is clearly demonstrated through visual interpretation and manual digitising on the standard FCC utilising various band combinations ranging from 1 to 4, as well as the incorporation of topographical maps from the Survey of India, 1962 (SOI). Knowledge of the visual interpretation key, the region's morphology, and even a good understanding of the reflectance curve combined helped to explain the different characteristics of the glacier, which finally helped to vectorize the glacial boundaries on satellite imagery. The distinctive signature of snow and ice, the shape of the glaciers in the valleys, the movement of ice in the glacier, the rugged texture of debris in the ablation areas, the association of the shadows with the steep mountain peaks, the vegetated parts of the mountains etc. all serve as a visual aid complementing the better perception of the glaciers.

Another way to differentiate and delineate the boundaries of the glacier is the grass that occurs during the August-September season in the lateral and terminal moraine areas, as well as around the snout that gives a red tone to the standard FCC. Many avalanches often occur in the neighboring cliff regions in this area, providing greater reflectance due to the dirty snow along the edges. As stated earlier, the Short Wave Infra-Red (SWIR) band is effectively used to differentiate between the cloud and the snow layer and the differentiation between the glaciated and the non-glaciated area in this band is therefore significantly sharper (Snow and Glacier Studies, 2010).

Accumulation Area

Accumulation area is the part of the glacier that has a perennial snow cover. For most glaciers, the main source of ice is precipitation in the form of snowfall, which varies from place to place. The method of redistribution by wind or avalanche in the zone of accumulation is more dominant on a local scale. The accumulation region is characterized by high winter snowfall relative to the summer ablation, which encourages the development of the glacier. It is fundamentally a very crucial element of the glacier, implying that the snow feed received accumulates over time and does not totally melt between seasons. In the standard FCC, the accumulation area appears white because its reflectance is high in all visible bands as well as in the Near Infra-Red (NIR) region. It can then be conveniently demarcated (Snow and Glaciers of the Himalayas, 2011; USGS).

Ablation Area

It is a region in the lower part of the glacier, i.e. lower altitude, marked by a net loss of mass (Hubbard and Glasser, 2005). The "Ablation Zone" is known as the zone where ablation exceeds accumulation rates (Young and Norby, 2009). The removal of glacial ice from the ablation region is caused by several factors such as wind ablation, avalanching, water calving, melting etc. in which melting becomes a dominant mechanism for glaciers where for a portion of the year the temperature exceeds 0°C. Thus, the accumulation of winter snow is lost as a result and the glacial ice is exposed. In the visible and the NIR (Near Infra-Red) zone, this has low reflectance and gives a green-white tone on the standard FCC that can be clearly separated from the accumulation area.

Statistics on the ablation region are significant as they reflect the area that is subject to active seasonal ablation. The ablation region is further categorized in the ice-exposed ablation area and the debris protected ablation area. Glaciers that are exposed to ice and free of debris cover have a smoother texture compared to glaciers with debris cover. Glacial ice in the ablation region is thought to remain secure from accelerated melting as it is surrounded by a layer of debris.

Moraine Dam Lakes

Moraine dam lakes, also known as pro-glacial lakes, are formed by the deposition of glacial melt water at the lower elevations of the glacier (Sharma, et al., 2013). Most commonly, these lakes were formed as a result of the dam impact of glacial moraines, though they were also known to occur in glacial valleys. These lakes have characteristic shapes and are found in front of the glaciers, which point to the lowest elevation point or where the glacier begins. On the satellite images, they can easily be recognized by their distinctive form and dark-blue and black hue. These dams are vulnerable to dam bursts and unexpected flooding in downstream areas. They are labelled as dangerous till they are connected to the ice, which supplies the lake with constant melting water.

Supraglacial Lakes

Supraglacial lakes form on the glacier surface using epiglacial behaviour within the ice mass away from the moraine, with diameters ranging from 50 to 100 metres. Supra glacial lakes can be easily detected by their high contrast with the glacier ice and debris in the satellite data. The signature characteristics of supra glacial lakes are moving, mixing, draining and vanishing (Raj & Kumar, 2016). In nature, these lakes are very complex as lakes of smaller size on glacier tongues appear to overlap and thereby grow over time. The successive merger of the Supraglacial lakes and the creation of a bigger lake can be described using temporal satellite images. These Supraglacial lakes activities are signs that the lakes are potentially hazardous. This results in the accumulation of a significant amount of water with a high potential energy level that indicates GLOF (Glacier Lake Outburst Floods).

Certain evidences show that such lakes intensify the disintegration of glacier ice by draining water into the ice gaps, melting the bottom of the glacier. (Benn et al., 2000, Richardson & Reynolds, 2000). This hydro-crack operation vertically and laterally enlarges supra glacial lakes and fragments the glacier at the terminus. In addition, the ice cliffs that form around the supra glacial lakes enhance the radiation level that the glacier gets. As a result of this disintegration and enlargement of the lakes, proglacial lakes arise from supraglacial lakes at the snout, bordered by ice-cored moraines (Govindha Raj et al., 2014).

De-Glaciated valley

Through the de-glaciated valleys and associated characteristics, a glacier's health can be evaluated. These valleys point at the melting valley glaciers that abandon their valleys below the snout area in the lower reaches. The moraine deposit type and the valley dimension are representative of the glacier's retreat trend. Using multi-date satellite data, it is possible to classify the changes and extent of the de-glaciated valley features (Snow and Glaciers of the Himalayas, 2011). They can also be seen impounded in between the disappearing glacier tongue and the end moraines in the multi-date satellite image and hence can be mapped.

Point Features

Certain features require elevation details and location in terms of latitude and longitude. Hence, they are mapped in the form of Point Layer.

Snout

The "snout" is referred to as the glacier terminus or the lowest glacier elevation point from where the melt water emerges (Singh, 2001). This is the section of the glacier ablation zone from which the river or stream emerges on the surface (Bahuguna, 2008). The snout of the glaciers shows different forms and features based on the height of the glaciers, the condition of the valleys, the bed rock slope and the mass balance of the glacier **(Singh, et al., 2011)**. The relative positions of various snouts on satellite images can be determined with the use of geomorphic features like as moraines, stream source points and even moraine-dammed lakes (Kulkarni, et al., 2007)

Glacier Elevation Point Locations

Highest and lowest point elevations for each glacier, moraine dammed lake elevations as well as elevation of the supra-glacier lakes had been taken from the Digital Elevation Model (DEM) grid. Layers containing point positions have been intersected with the DEM layer generated using SRTM data to extract elevation information for each point.

Line Features

Features like the length of the glaciers and lakes, the ice-divide line and the equilibrium line all need to be mapped as lines as we need their length measurements and their position on the Final Glacier Map.

Equilibrium-Line Altitude (ELA)

The altitude of the equilibrium line symbolizes the area or region on a glacier that divides the zone of accumulation from the zone of ablation and is symbolic of the zone where annual accumulation and ablation are almost equal (Singh, et al., 2011). The terms transient snow line and equilibrium-line are considered to be the same and are used at the end of the melt season to measure the mass balance. The minimum extent of snow cover is compared and taken from the two sets of data during the transient snow line measurement.

Ice Divide Line

Basically, the ice divide lines are lines of separation between two or more neighboring glaciers. It is characterized by the movement of the ice in two separate directions. The Himalayan ice divide is connected to the cliffs of the mountains, so the delineation can be conveniently done using the cliff shadow. The amount of shadow that is cast by the cliff is influenced by different variables such as solar elevation, azimuth and cliff direction. The orientation of the cliff is very important since it is possible to detect full shadow as the cliff lies perpendicular to the sun's azimuth (Kulkarni, 2001). The ice divide was identified and then manually digitized through visual inspection of SRTM DEM with a hill shade effect. The acquisition time for the IRS is almost an hour later than for the Landsat satellite. Therefore, TM images show more distinct shadows than images from LISS-III. Thus, if required, Landsat images could also be used.

3.3:- Mapping of Glaciers

Various glacier features were mapped using the above-mentioned characteristics. The mapping was carried out at a scale of 1:50,000 and therefore separate layers prepared by the analysis of multi-date satellite data were properly codified and processed in the GIS setting in the digital database. The technique of codifying glacial features is outlined in Chapter 1 and the codes are discussed in Table 1.11. The Figure (3.3) below represents the structure of a Glacier Datasheet. This is how the data was entered and all parameters were covered for all the glaciers of Sikkim and Bhutan.

Figure 3.3: Sample Glacier Inventory Data Sheet

GLAC ID	78A15006	LEN_MAX_AB	20.33	DATE SNLIN	03/01/2008
GLAC NAME		ORIENT AC	E	MEAN DEPTH	40
LAT	30.68	ORIENT AB	E	DEPTH ACRC	1
LONG	93.17	MAX_ELEV	7282	COUNTRY	IN
COORDINATES	UTM WGS84	MEAN_ELEV	5687	CONTINENT	05
NUM BASINS	1	MIN ELEV	4092	BASIN CODE	030000000000
NUM STATES	1	MIN EL EXP	5014	SAT NAME	IRS P6
TOPO SCALE		MEAN EL AC	6256	SAT SENSOR	AWiFS
TOPO_ YEAR		MEAN EL AB	4661	SAT_PASS	03/01/2008
PHOTO_ TYPE		CLASS	5	SAT_DATA_TY	DIGITAL
PHOTO_ YEAR		FORM1	1	SAT BANDS	234&5
TOTAL AREA	155.7	FRONT	0	DGV LENT	
AREA ACU	106.35	LONG PROF	0	DGV AREA	
AREA STATE	155.7	SOURCE	1	DGV_MIN_EL	
AREA_ EXP	19.74	TONGUE_ACT	3	LAKE_TYPE	
AREA_AB	49.35	PERIOD1	15/09/2004	LAKE_AREA	
WID ME AB	0.800025	PERIOD2	03/01/2008	LAKE ELEV	
LEN ME AB	11.65	MORAIN1	0	COMPIL NAM	Vanya Bajpai
LEN MAX	28.43	MORAIN2	8	ORGANISA	MSU
LEN_ MIN	2.327339	EL_SNLIN	5230	DATE	26/03/2015
MEAN_LEN	15.38	SNLINE_ACU	1	REMARKS	
LEN_MAX_EX	4.512164				

Source: - Computed

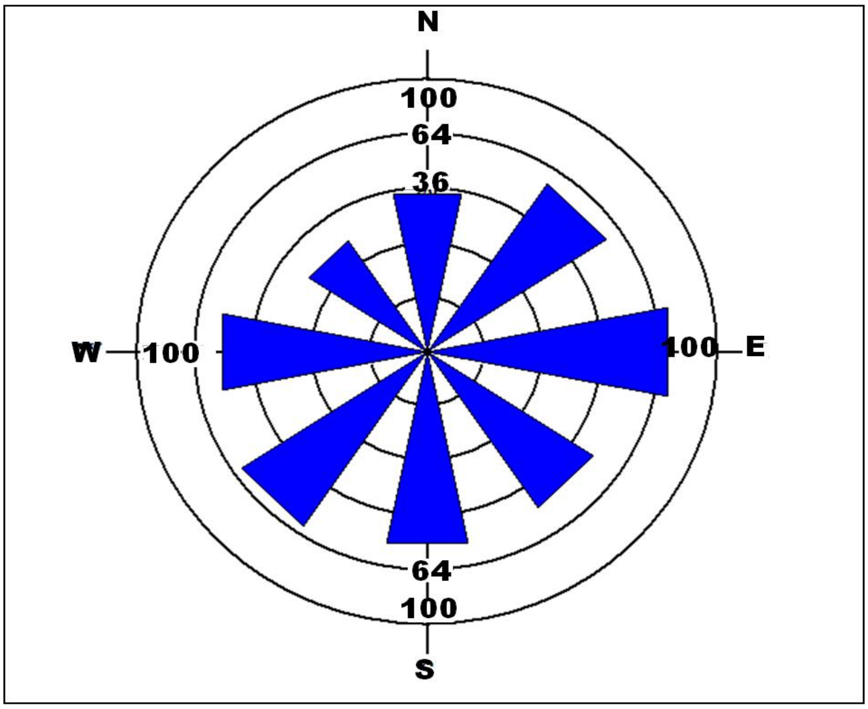
3.4:- Estimation of Glaciers of Sikkim

The glacier inventory map for the Sikkim (Tista sub-basin) illustrates the location of glaciers and their spatial distribution. The mapped glacier characteristics include the glacier boundary, which shows the area of each glacier, as well as its morphological subdivisions, such as ablation and accumulation zones.

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). The smallest glacier, 0.13 square kilometre in area and the largest is 155.7 square kilometre. According to Ives and Barry, 2019, glaciers found in the Northern Hemisphere and south-facing slopes seem to melt more quickly than those with north-facing slopes. This fact 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, whereas a few face towards the west and south- west (Figure 3.4). As a result, since the majority of the glaciers in this sub-basin face north-east and east, they are less sensitive to melting caused by direct sun radiation.

Figure 3.4. Glacial Orientation of Sikkim (Tista Sub-Basin)

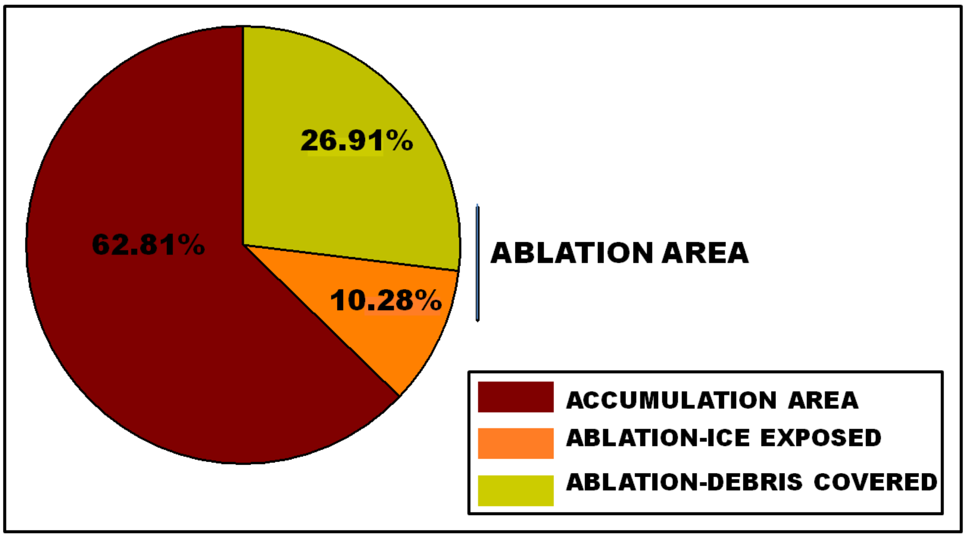


Source: Computed

The entire accumulation area of the glaciers is 815.67 square kilometres, which is much bigger than the total ablation area of 491.41 square kilometres, which includes ice exposed and debris-covered regions (Figure 3.5). While it was measured that the ablation area obscured by debris was larger (355.53 square kilometre) than the ablation area covered by ice (135.88 square kilometre). Thermal conductivity (or thermal resistance) and albedo are the primary physical properties of a debris layer that regulate heat transfer to the ice-debris surface. As a result, as the thickness of the debris grows, heat transmission to the glacial ice decreases, lowering the rate of ablation. (Ostrem, 1959; Loomis, 1970; Fujii, 1977; Mattson & Gardner, 1989; Rana et al., 1997). This elucidation reinforces the fact that the glaciers in this basin are more or less stable, as can be seen in Figure 3.5.

The findings of the inventory are depicted in the final inventory map (Fig. 3.7) and table (Table 3.1), 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 metre), Mt.Kabru (7381 metre), Mt.Siniolchu (6888 metre), Mt.Simvo (6851 metre), Mt.Pandim (6736 metre), Mt.Rathong (6736 metre) and Mt.Kokthang (6145 metre) are situated to the west of Sikkim. Thus, giving the glaciers an appropriate environment to form and grow. This is also one of the reasons that most of the glaciers in the western part of the sub-basin have "Compound Basins".

Figure 3.5. Accumulation and Ablation Percentage Area share in Sikkim (Tista Sub-Basin)



Source: Computed

There are 220 “Simple Basins” with a single accumulation area, suggesting that the maximum glaciers in this sub-basin are small, varying from 0.13 square kilometre to 5.39 square kilometre (Inventory, 2006). Glaciers with a "Compound Basin," on the other hand, are created when two or more individual accumulation basins feed one glacier system they are formed when two or more individual valley glaciers arising from tributary valleys coalesce.In the Sikkim/Tista sub-basin there are 151 of them, varying in size from 30.18 square kilometre to 23.62 square kilometre. Compound Basins the lowest in number in the Sikkim Basin (23), but have the largest area (ranging from 3.43 square kilometre to 155.75 square kilometre).

Table 3.1. Results of Glacier Inventory of Sikkim (Tista Sub-Basin)

Sr. No.	**Basin Characteristics**	**Basin Statistics**
1	Total Number of Glaciers	394
2	Glaciated Area	1321.40 km^2
3	Accumulation Area	815.67 km^2
4	Ablation Area Debris	355.53 km^2
5	Ablation Ice Exposed	135.88 km^2
8	No. of Supra - Glacier Lakes	44
9	Area Under Supra - Glacier Lakes	10.73 km^2
10	No. of Moraine Dam / Glacial Lakes	3
11	Area of Moraine Dam / Glacial Lakes	3.77 km^2
12	Volume of Ice	146.74 km^3
13	Water Equivalent	127.66 km^3
14	Accumulation Area Ratio (AAR)	0.62

Source:- Computed

When both the glacial area and temperature are lower, more bare soil surrounding the glacier is exposed, reducing the albedo of the area, allowing more solar radiation to be absorbed, warming the micro - climate and speeding up glacier melt (Ives and barry, 2019). This fact emphasizes the significance of glacier elevation and location. It is also computed that, the lowest snout elevation in the Tista sub-basin is 2837 metre, while the maximum snout elevation is 5704 metre. The glacier's highest elevation point in this basin is 2961 metre, and it rises to 7282 metre. Along with the highest and lowest elevation points of the glaciers, the snowline (a point above which snow does not melt in summer) is also an important parameter that should be considered. The average snowline elevation of the Tista sub-basin is 4853 metre, falling within the range of the Himalayan snowline between 4800 -6000 metre which gives us an indicator of the good health of the glacier.

It's worth noting that this sub-basin had 44 "Supra-Glacier Lakes" covering 10.73 square kilometre and two "Pro-Glacial or Moraine Dammed Lakes" covering 3.59 square kilometre. The Tista sub-basin, which is dotted with several "supra-glacier" and "pro-glacial lakes," is continuously endangered by **G**lacial **L**ake **O**utburst **F**looding (GLOF). These floods occur when the terminal moraine dams collapse, posing a threat to the local human population. A natural disaster occurred on August 4, 1985 in the Dig Tsho (Tsho-lake), in the western portion of the Sagarmatha (Mt. Everest) National Park, Khumbu Himal, Nepal, supporting this fact of GLOF. The moraine was breached, releasing 8 million cubic metres of water downstream, destroying the Namche Small Hydel Project and killing five people (Bajracharya, S.R. et al., 2007).

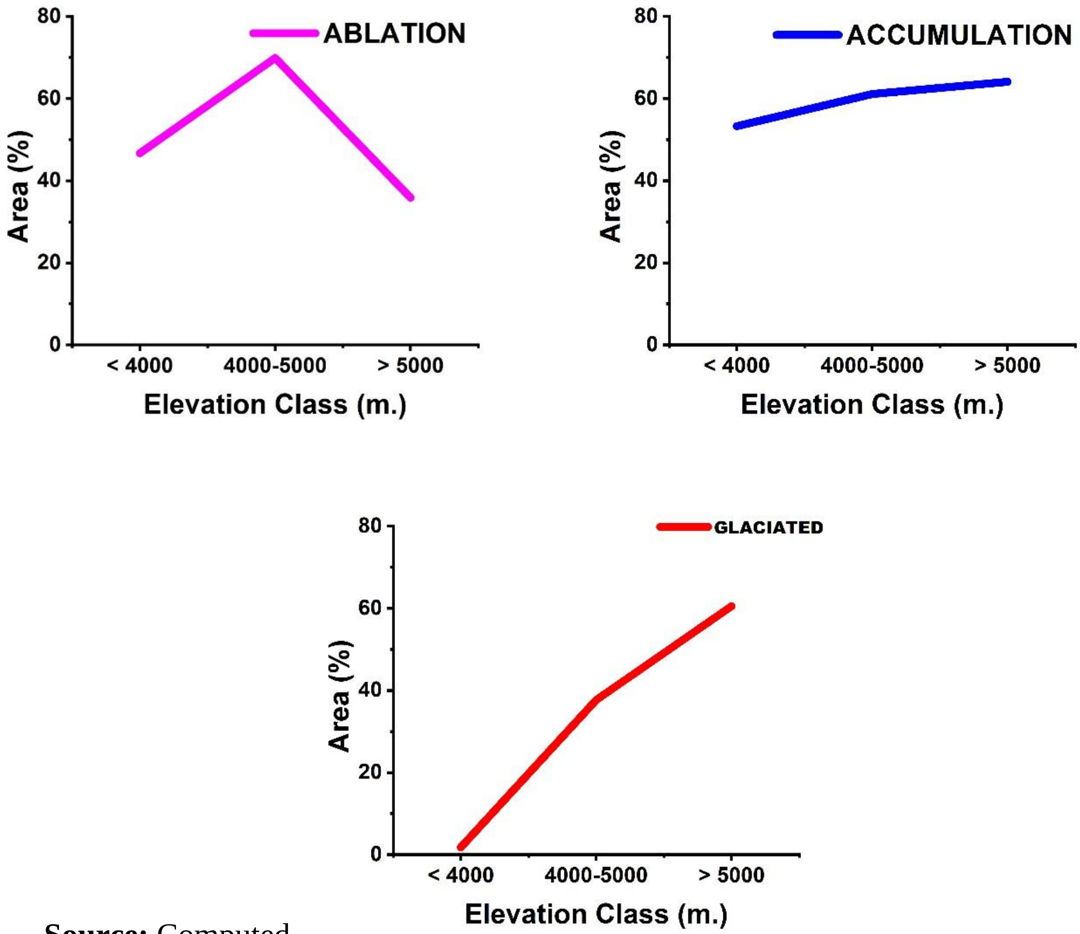
The “Accumulation Area Ratio” (AAR) of Tista Sub-basin is relatively high (0.62) (Scherler, D. et al., 2011) suggesting that the glaciers in this basin undergo relatively less melting and the glaciers are deemed to be "in equilibrium." The overall "Volume of Ice" trapped in the glaciers was approximately 146.14 kilometre^3, as measured using the equation devised by Chaohai and Liangfu (1986) and Shi (2008). This number is important for modeling glacier responses to climate change and also shows the vast amount of water concentrated in these glaciers.

Elevation Wise Glacier Estimation

This study seeks to analyze the glaciers of Sikkim considering elevation groups of < 4000 metre, 4000-5000 metre, and > 5000 metre. The major characteristics of the glaciers would be discussed and compared keeping their altitudinal range in mind.

In the elevation classes of < 4000 metre and >5000 metre debris covered area (90.27% and 66.61% respectively) which was more than the ice-exposed region (9.72% and 33.10% respectively). On the other hand, in 4000-5000 metre elevation class ablation area ice exposed was higher (55.60%) than the ablation area debris covered (44.40%) owing to which ice-exposed region of glaciers falling in this category were susceptible to faster melting with consideration to their altitudinal and geographical positions.

Figure 3.6. Sikkim - Elevation Class Wise Distribution of Total Glaciated, Accumulation and Ablation area



Source: Computed

As seen in Table 3.2 the total accumulation area was least (53.32 %) in the < 4000 m elevation category, in comparison to the accumulation areas of other elevation categories of 4000-5000 metre (61.14 %) and > 5000 metre (64.13 %).The total area under ablation in

>5000 metre class was 35.87% followed by the elevation class of 4000-5000 metre (38.86%) and <4000 metre (46.68%). These statistics indicate the fact that glaciers located in the elevation class of >5000 metre had higher accumulation area and less ablation area. As exposure to direct sunlight is less in these areas thus less melting was experienced. In the < 4000 metre elevation category the accumulation and ablation zones were almost similar (accumulation area 53.32% and ablation area 46.68%), underlining the fact that glaciers in this region do not denote either a positive or a negative mass balance (Figure 3.6). This assertion was supported by the fact that, even after the melting season and heavy flow at the terminus, if the glacier has more than 60% of the area under snow and wide accumulation areas, the glacier is supposed to be in a 'healthy' state.

There were a sixteen (16) **S**upra **G**lacial **L**akes (SGL) in the 4000-5000 metre elevation glacier category and cover 0.21% of the total glaciated area. 47 supra glacial lakes occupied roughly 1.22 percent of the entire glaciated terrain in the elevation category >5000 metres. On the other hand, there was no record of Moraine Dammed lakes in other elevation classes except in the >5000 metre category where an area of about 0.47% of the total glaciated area was occupied by 3 large lakes.

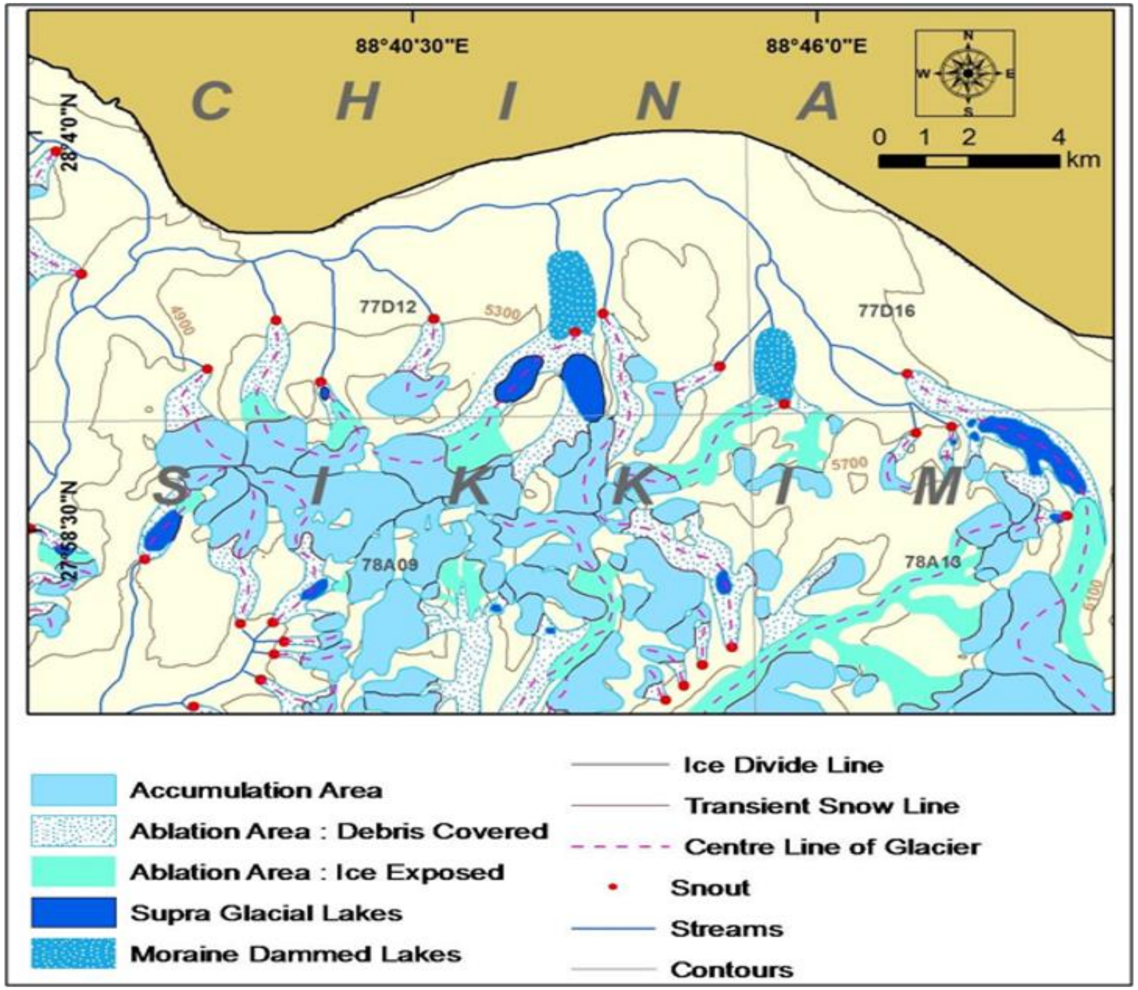
Figure 3.7 is the glacier inventory map of Sikkim that shows the point, line and polygon features of the glaciers like accumulation, ablation – debris and ice-exposed areas, the snout, moraines, etc. Figure 3.8 shows the total glaciated area of Sikkim and also the Tista River and its tributaries.

Table 3.2:-Sikkim - Elevation Class-Wise Statistics

Sr. No.	Class	Glaciers (%)	Total Glaciated Area (%)	Accumulation Area (%)	Ablation Area (%)			Supra Glacial Lake		Moraine Dammed Lake	
					Debris	Ice Exposed	Total	No.	Area (%)	No.	Area (%)
1	< 4000	5.58	1.77	53.32	90.27	9.72	46.68	0	0	0	0
2	4000 – 5000	62.69	37.67	61.14	44.40	55.62	38.86	16	0.21	0	0
3	> 5000	31.73	60.56	64.13	66.61	33.10	35.87	47	1.22	3	0.47
	Total	**100**	**100**					**63**		**3**	

Source: Computed

Figure 3.7. Glacier Inventory Map of Sikkim (Tista Sub-Basin)



Note: This Figure represents the Final Glacier Inventory Map of Sikkim elucidating all the point, line and polygon features mapped.

Source: Computed

Figure 3.8. Glaciated Region of Sikkim (Tista Sub-Basin)

Source: Computed

Conclusion

The inventory of the Sikkim/Tista sub-basin in the Brahmaputra basin provides information about the many characteristics found within the glaciers. All glacier properties were computed in great detail. The manual digitization of glacier length was the most time-consuming process. Parameters such as glacier orientation, maximum and minimum elevation, maximum and minimum width of glaciers and so on give extra information that is highly valuable for practical applications.

With 31.73% glaciers, Sikkim had the largest glacial concentration in >5000 m category i.e. 65.56% of the total glacial area. Elevation category of 4000-5000 m recorded the highest glacier concentration in Sikkim i.e. 62.69%. It was also noted that the average glacier size in the study areas was the lowest in <4000 m elevation class. These outcomes very well point towards the fact that there is a marked increase in the glacial size and also number as we progress towards the higher altitudes.

Thus, inventory providing such huge database is a very important asset in the world of glaciers. The results of this database can be used to update the Himalayan glacier database, providing more information to researchers working for glacier dynamics and climate change.

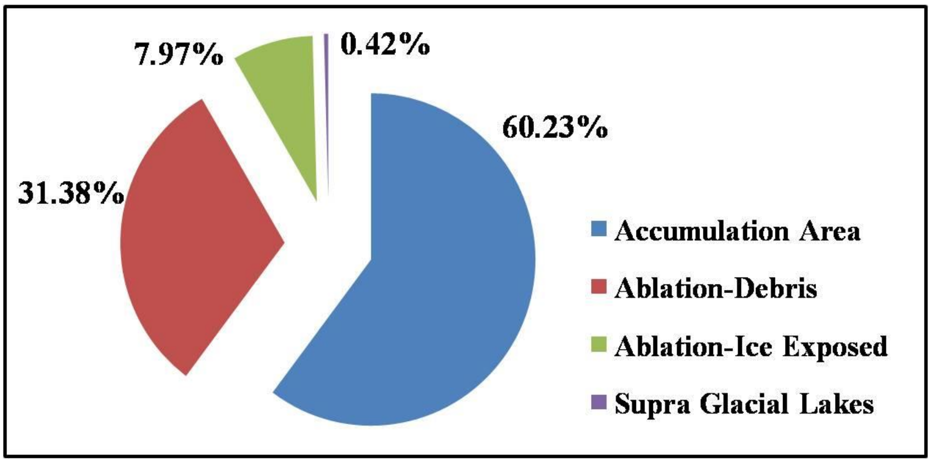
3.5:- Estimation of Glaciers of Bhutan

Glacier Inventory of Bhutan represents the glacial status of the time when the glaciers were mapped. It was a compilation of 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.

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 kilometre (Table 3.3.) 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 kilometre to very large "Compound Basins" glaciers of 121 square kilometre. The entire accumulation area was (2229.71 square kilometre) 60.22% of the whole glaciated area, which was much more than the total ablation area of the basin, that was 39.34 % (1456.49 square kilometre) of the glaciated region. The ablation area-debris covered i.e. 79.76% (1161.62 square kilometre) was much higher than the ablation area – ice exposed i.e. 20.25% (294.87 square kilometre) pointing towards the overall stability of these glaciers.

Figure 3.9. Sub-Basin Characteristics of Bhutan



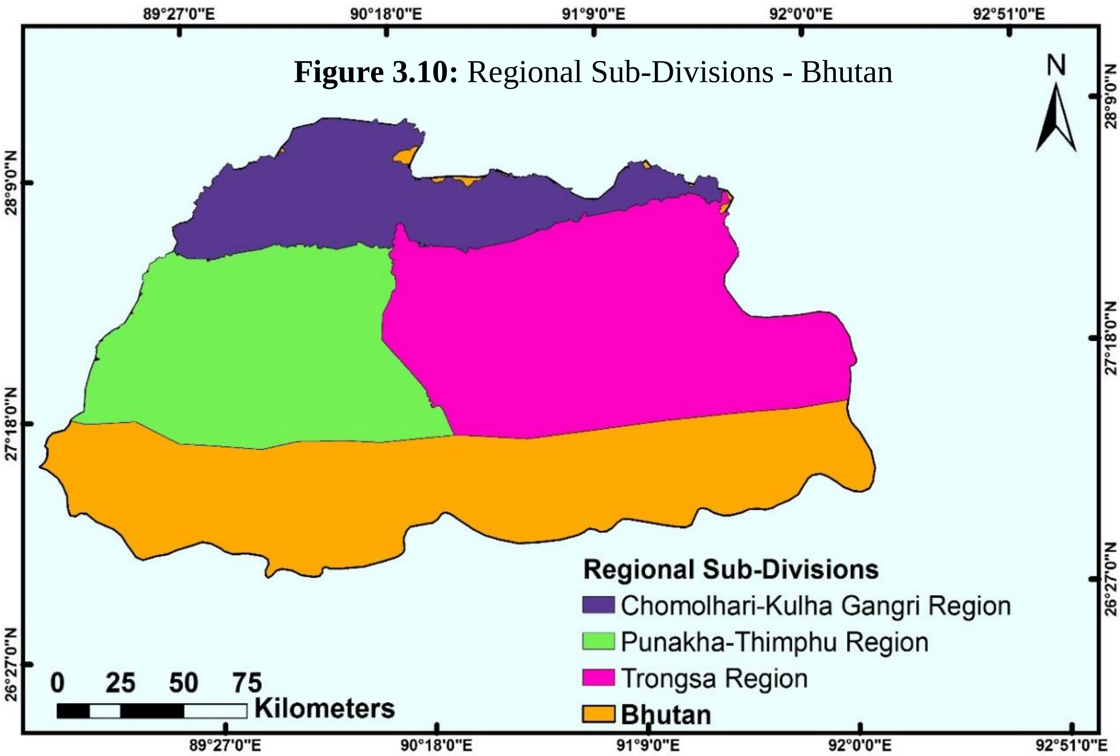
Source: Computed

Table 3.3. Broad Approach for Glacier Inventory and Datasheet of Bhutan		
Sr. No.	**Basin Characteristics**	**Basin Statistics**
1	Total Number of Glaciers	1151
2	Glaciated Area	3702.33 km^2
3	Accumulation Area	2229.71 km^2
4	Ablation Area	1456.49 km^2
5	Ablation Area Debris	1161.62 km^2
6	Ablation Ice Exposed	294.87 km^2
7	No. Of Supra – Glacier Lakes	60
8	Area Under Supra – Glacier Lakes	0.42 km^2
9	No. Of Moraine Dam / Glacial Lakes	3
10	Area Of Moraine Dam / Glacial Lakes	7.91 km^2
11	Volume Of Ice	405.78 km^3
12	Water Equivalent	353.03 km^3
13	Accumulation Area Ratio (AAR)	0.60
Source: Computed		

The study area was dotted with numerous small supra-glacial lakes. A total of 60 lakes were mapped covering an area of 0.42% of the total glaciated area (Figure 3.9), indicative of the fact that though large in numbers but these lakes cover a very small part of the glaciated region. Only three (3) but large Moraine Dammed lakes were recorded in Bhutan accounting for of 7.91 square kilometre area.

Glaciers with single accumulation area which are classified as "Simple Basins" are maximum in Bhutan i.e. 824. They cover an area of about 1120.73 square kilometre which points towards the fact the glaciers in the sub-basin have smaller glacier area. In general their size vary from 0.11 to 18.35 square kilometre. The largest glacier with the maximum area having a Simple Basin had 51.32 square kilometer coverage. On the other hand, glaciers having "Compound Basin" i.e. with two or more individual accumulation basins were 298 in number covering an area of about 1355.19 square kilometer. They vary in size from 0.36 to 16.55 square kilometre. "Compound Basins" were the lowest in number where only 29 glaciers fell into this category covering an area of about 1226.41 square kilometre. Though less in number, the average size of the glaciers can be computed to 42.29 square kilometre. The smallest glacier in this category covered an area of about 13.68 square kilometre as opposed to the largest glacier with 121 square kilometer area.

Figure 3.10: Regional Sub-Divisions - Bhutan



Source: Computed (Singh, 2008)

Region wise Glacier Estimation

Geomorphologically, the topography of the study area is quite sketchy, from the subtropical plains in the south to the sub alpine snowcapped ranges in the north attaining heights of more than 7,500 metre (Cenral Intelligenge Agency, 2015) R.L. Singh's (Singh, 2008) regional sub-divisions were thus adopted here. By splitting Bhutan's glaciated areas into three primary physiographic divisions, the regional scenario becomes comprehensible (Figure 3.10).

Chomolhari-Kulha Gangri Region (North):

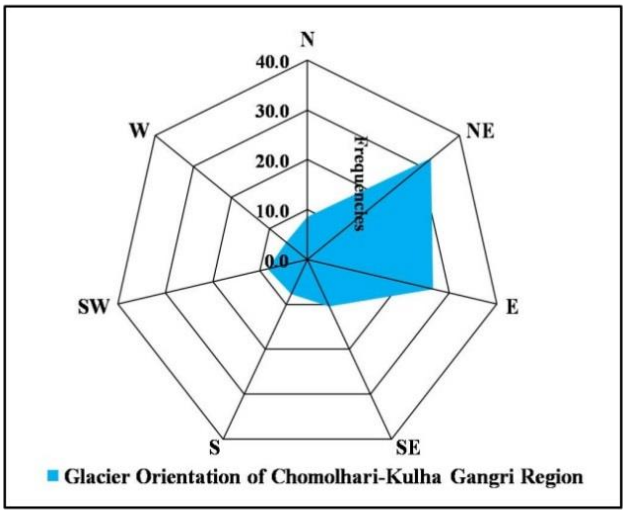
Since this region is situated in the Greater Himalayas, the number of glaciers documented was the highest (432), with a large glaciated area (2471.46 square kilometre). In this zone, the total area of accumulation (62.73 per cent) surpassed the total area of ablation (36.97 per cent) (Table 3.4). Supra Glacial Lakes in the Chomolhari region, despite their large numbers (43) were not a possible threat for lake outbursts because they occupied a very small area of around 0.51 percent. The Rose diagram (Figure 3.11) plotted to display the orientation of the glaciers showed that about 41.20 percent of the glaciers were aligned north-east and east.

Table 3.4: Glacier Statistics of Chomolhari - Kulha Gangri Region

Number of Glaciers	432
Glaciated Area (sq. km.)	2471.46
Accumulation Area (%)	62.54
Ablation Area (%)	36.97
No. of Supra Glacial Lakes	43
Supra Glacial Lakes (%)	0.51

Source: Computed

Figure 3.11: Glacier Orientation of Chomolhari-Kulha Gangri Region



Source: Computed

Trongsa Region (West):

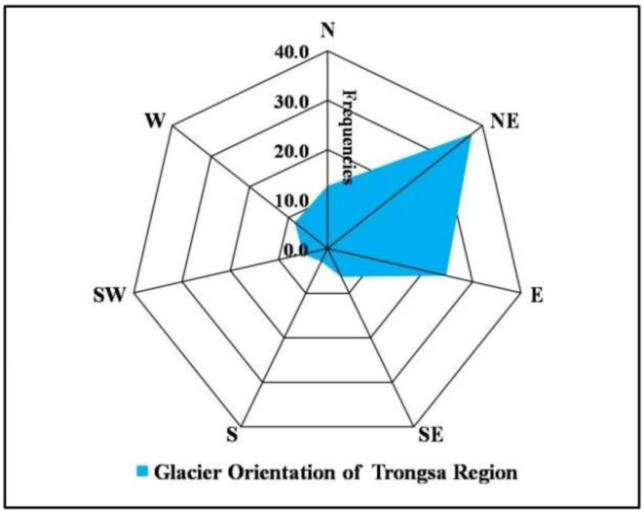
With 378 glaciers and a glaciated area of 594.87 square kilometers, this district, in line with the Sikkim Himalayas, had the second highest number of glaciers in Bhutan. The area of accumulation was area of accumulation was 55.70 %, while the area of ablation was 43.76 %. In contrast to the Chomolhari-Kulha Gangri district, supra glacial lakes were the second most widespread (10) and covered a greater area (0.37 %) (Table 3.5). Once again, the majority of the glaciers were oriented to the north-east (approximately 37.30 %) and east (approximately 34.60 %) and 48 glaciers were oriented to the north (Figure 3.12).

Table 3.5.: Glacier Statistics of Trongsa Region

Number of Glaciers	378
Glaciated Area (sq. km.)	594.87
Accumulation Area (%)	55.70
Ablation Area (%)	43.76
No. of Supra Glacial Lakes	10
Supra Glacial Lakes (%)	0.37

Source: Computed

Figure 3.12: Glacial Orientation of Trongsa region



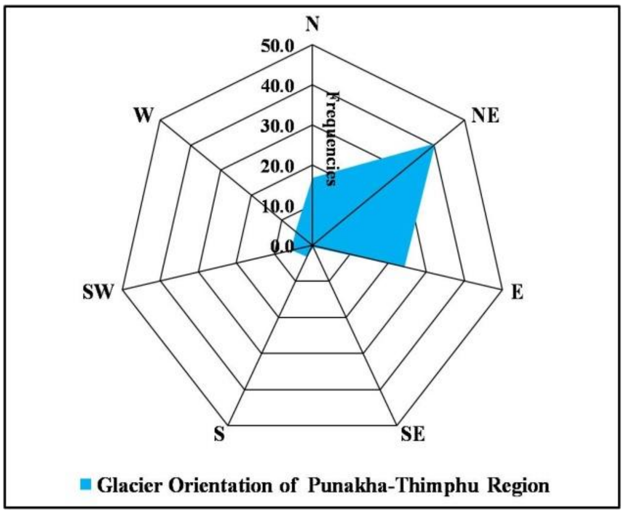
Source: Computed

Punakha-Thimphu Region (East):

This region, situated in the eastern part of the Kingdom of Bhutan, had the lowest number of glaciers (341), but the overall glaciated area was larger (636 square kilometre) than the Trongsa region. This indicates that the Punakha-Thimphu region's average glacier size is larger than that of the Trongsa region (Figure 3.13). The ablation area was estimated to be 44.41 % and the accumulation area to be 55.47 %. Supra glacial lakes were the smallest in this region, accounting for 0.12% of the total area. The majority of the glaciers in this area (40.47 %) were aligned north-east, followed by east and north oriented glaciers (Table 3.6.).

Table 3.6: Glacier Statistics of Punakha-Thimphu Region	
Number of Glaciers	341
Glaciated Area (sq. km.)	636.00
Accumulation Area (%)	55.47
Ablation Area (%)	44.41
No. of Supra Glacial Lakes	7
Supra Glacial Lakes (%)	0.12
Source: Computed	

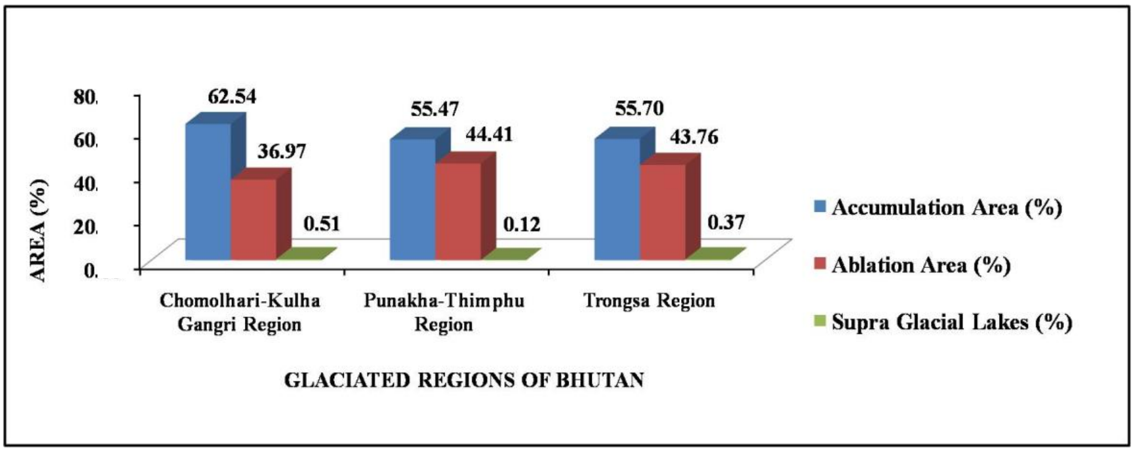
Figure 3.13. Glacial Orientation of Punakha - Thimphu Region



Source: Computed

Thus, making a comparative analysis (Figure 3.14.) of all the three physiographic regions, it can be concluded that the Chomolhari Region had the highest number of glaciers (432) followed by the Trongsa Region (378) and Punakha Region (341). Though the number of glaciers did not have a huge difference but the glaciated area of the Chomolhari Region was 2471.46 square kilometre as compared to the Trongsa (594.87 square kilometre) and Punakha (636.0 square kilometre) regions pointing towards the large glacial size in the northern most region of Chomolhari. The morphometric analysis shows that accumulation area was the highest in the Chomolhari-Kulha Gangri Region (60.54%), whereas both the other regions had almost the same accumulation areas (Punakha-Thimpu Region - 55.47% and Trongsa Region - 55.70%). Though the Chomolhari Region had the highest accumulation area but the ablation area was significantly less (36.97%) in comparison to the Trongsa Region (43.76%) and Punakha-Thimpu Region (44.41%). The Supra Glacial lakes occupied the maximum area in the Chomolhari Region (0.51%) followed by Trongsa Region (0.37%) and Punakha Region (0.12%). Since the accumulation area was much greater than the ablation area (Dixon, et al., 2015), this statistical study represented in the graph showed that positive mass balance occurred in this region. The rose diagram findings were thus attributed to the assumption that North facing glaciers increase in thickness (although some do decline, albeit at a slower rate) than South facing glaciers (Phan, et al., 2014).

Figure 3.14: Comparative Analysis of Glaciated Regions of Bhutan



Source: Computed

Region wise Estimation of Accumulation Area Ratio (AAR)

The Area Accumulation Ratio, or AAR, is a typical mass balance measure (Østrem and Brugman, 1991). The AAR is calculated by dividing the accumulation area of the glacier by the total glacier area (Paterson, 1994). It should be remembered that debris-free glaciers have an AAR of 0.5 to 0.8, whereas debris-covered glaciers have an AAR of 0.3 to 0.5. This is also the widely used AAR for Himalayan glaciers. (Benn and Evans, 2010). For this study AAR, (which is the AAR = Accumulation area / Glacier Area) has been computed for all the glaciers of Bhutan and then AAR has been plotted against the latitude and longitude of Bhutan and also against the mean elevation to study the trends.

Interpretation of AAR of Punakha-Thimpu Plotted Against Lat/Long and Mean Elevation

The Figure 3.15 gives an idea of distribution of the AAR of the Punakha-Thimpu against the glaciers according to latitude and longitude. It was observed that the low to mid latitude and low to mid longitude areas had the highest number of glaciers with Negative Mass Balance. Whereas, on the other hand high latitude areas had roughly equal number of glaciers with Negative Mass Balance and Steady State of Mass Balance areas. Positive Mass Balance of glaciers was recorded in very few areas which mostly lie in the high latitudes and high longitudes region. Negative Mass Balance and Steady State of Mass Balance were so evenly distributed over the region, with few outliers of Steady State of Mass Balance in low latitude and rising longitude zones.

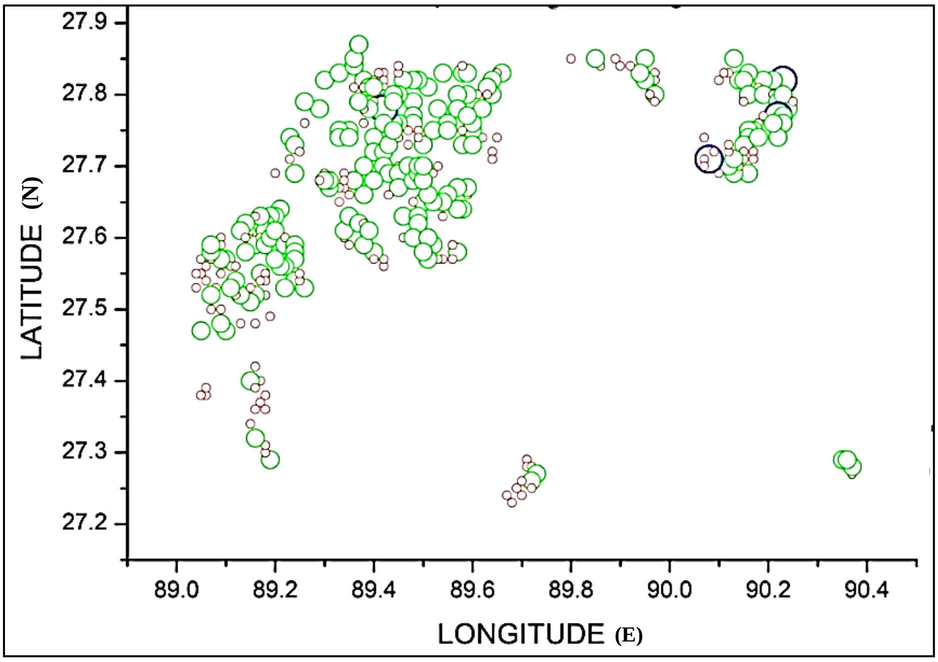
Table 3.7. AAR Classwise Distribution of Glaciers of Punakha-Thimpu Region

	Class	Frequency of Glaciers
Negative Mass Balance	< 0.5	159
Steady State	0.5 - 0.8	178
Positive Mass Balance	> 0.8	4

Source: Computed

The Figure 3.16 representing AAR plotted against mean elevation for the Punakha-Thimpu region it was observed that glaciers with the maximum frequency lie in the AAR class of 0.5 – 0.8 i.e. the steady state. Followed by 159 glaciers in <0.5 AAR class representing Negative Mass Balance while glaciers with Positive Mass Balance i.e. in the >0.8 class were very few (Table 3.7.). Maximum glacial concentration was in the 4200 metre to 4800 metre elevation. Some outliers can be seen where glaciers have an AAR of >0.8 and fall in the elevation category of 4200 metre to 4800 metre.

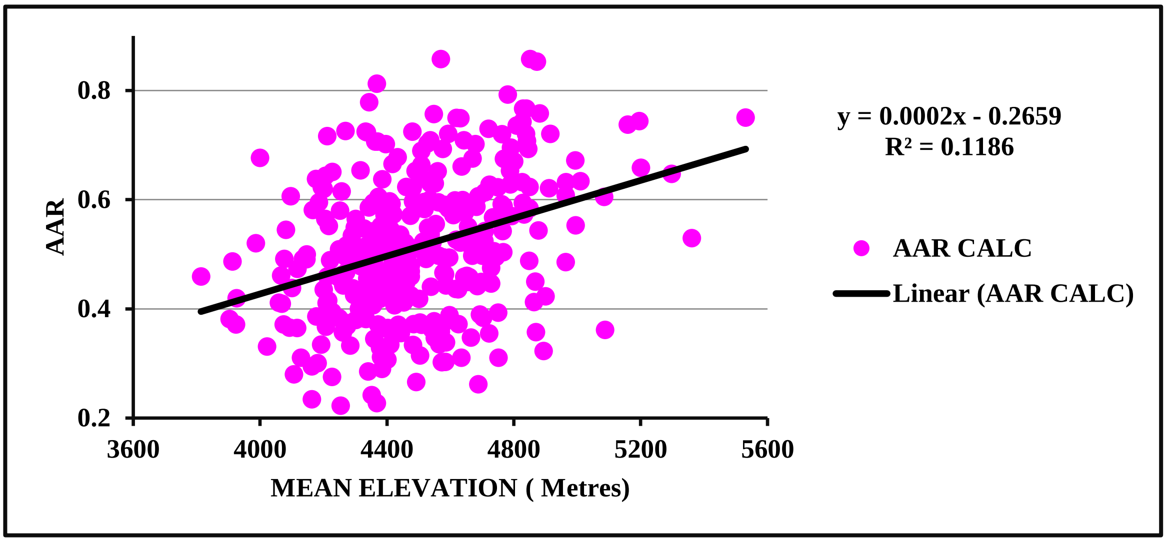
Figure 3.15: AAR of Punakha-Thimpu Plotted Against Lat/Long



Negative Mass Balance **Steady State** **Positive Mass Balance**

Source: Computed

Figure 3.16: AAR of Punakha-Thimpu Plotted Against Mean Elevation



Source: Computed

Interpretation of AAR of Trongsa Plotted Against Lat/Long and Mean Elevation

The AAR plotted against latitude and longitude for the Trongsa region clearly indicates that the low latitude and low longitude areas had approximately equal frequency of glaciers with Negative Mass Balance and glaciers in Steady State (0.5 - 0.8). Majority of the glaciers lying in the mid latitude that is within 27°21" to 27°40" have Steady State of mass balance followed by glaciers with Negative Mass Balance. Out of the 16 glaciers with Positive Mass Balance 4 glaciers were recorded in the mid latitude region. Glaciers with Positive Mass Balance were recorded mostly in the high latitude but low longitude areas.

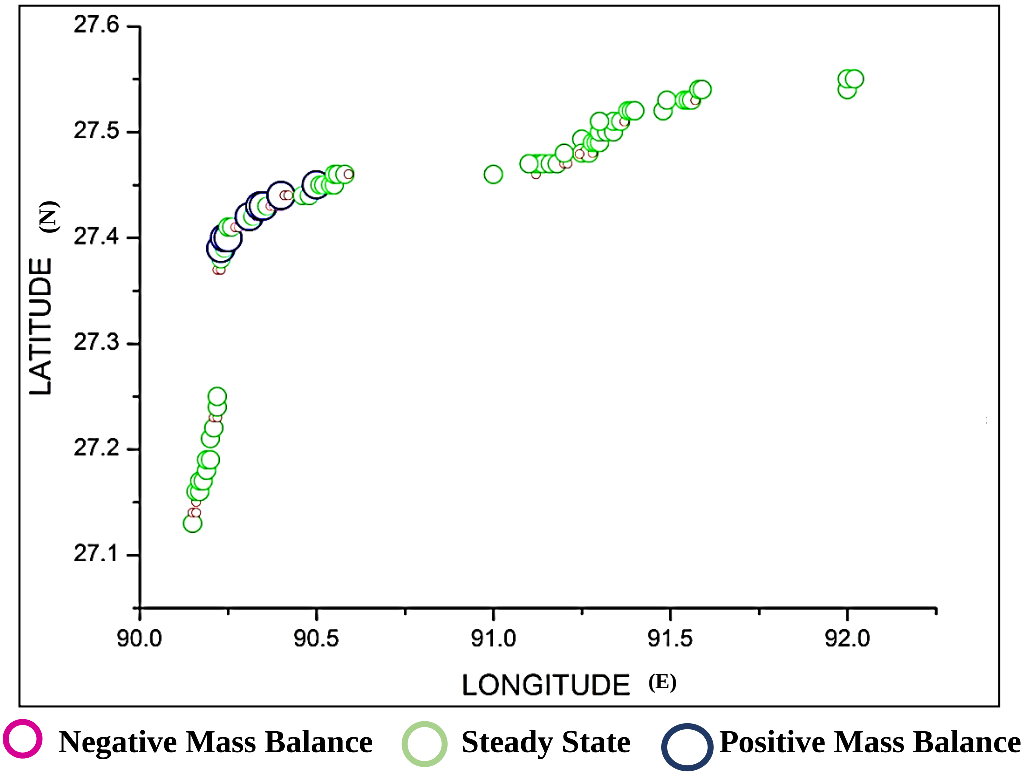
Glaciers having a Steady State of Mass Balance were the highest in number than the glaciers with Positive or Negative Mass Balance with most of their concentration on the high latitude regions. In comparison to the Punakha-Thimbu Region, Trongsa Region had higher number of glaciers having Steady Mass Balance and also Positive Mass Balance. Thus, through this data it can be said that the glaciers lying in this region are in good health relatively (Table 3.8).

AAR plotted against Mean Elevation (Figure 3.18) for the Trongsa shows that maximum i.e. 214 glaciers are in a Steady State (0.5-0.8) followed by 148 glaciers having Negative Mass Balance (<0.5) (Figure 3.17). The maximum concentration of glaciers was observed from 4000 metre to 4400 metre elevation. The frequency of glaciers lying in the

Positive Mass Balance category were very few (16) having an AAR of >0.8. But their concentration was also around 4000 metre to 4600 metre elevation category. A few outliers can also be noticed where the AAR is more than 0.60 but they are concentrated from 3200 metre to 3600 metre elevation.

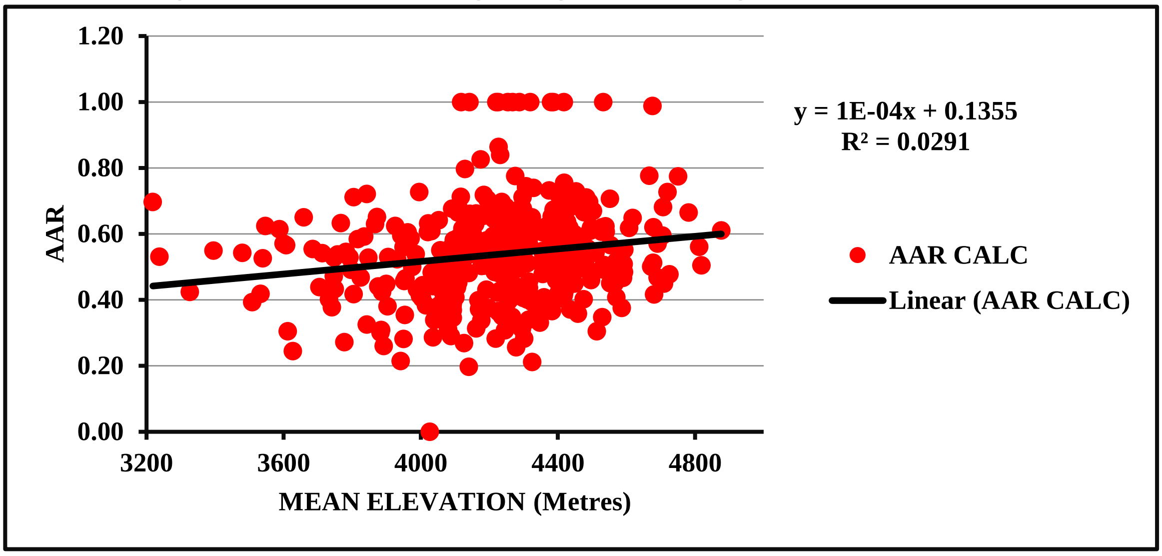
Table 3.8. AAR Classwise Distribution of Glaciers of Tongsa Region		
	Class	**Frequency of Glaciers**
Negative Mass Balance	< 0.5	148
Steady State	0.5 - 0.8	214
Positive Mass Balance	> 0.8	16
Source: Computed		

Figure 3.17: AAR of Trongsa Region Plotted Against Lat/Long



Source: Computed

Figure 3.18: AAR of Trongsa Region Plotted Against Mean Elevation



Source: Computed

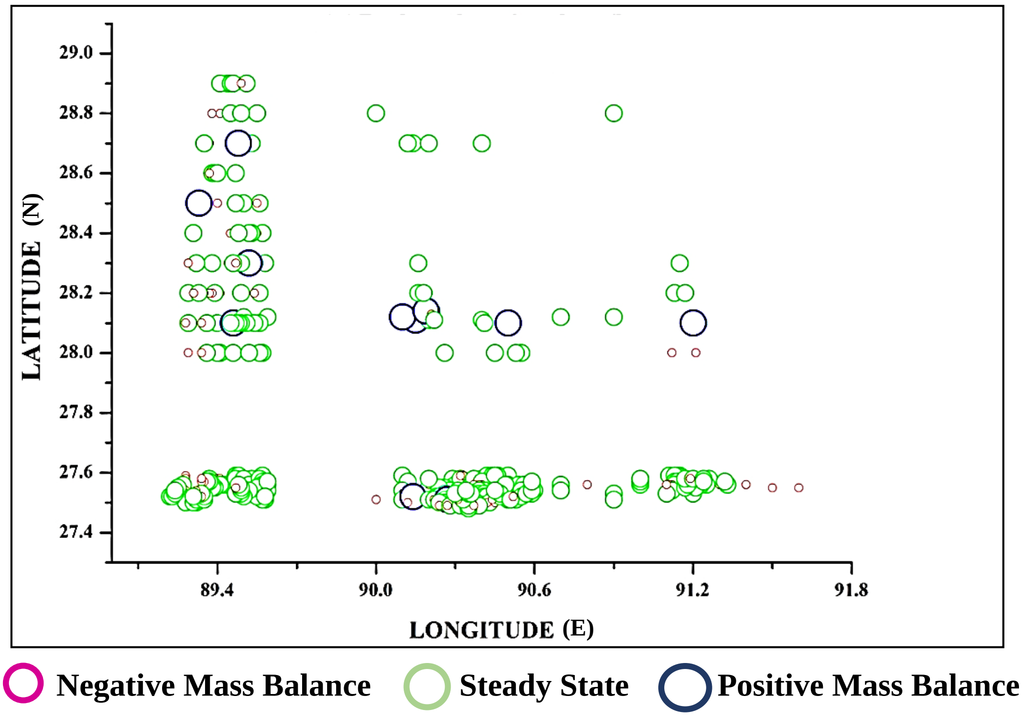
Interpretation of AAR of Chomolhari-Kulha Gangri Plotted Against Lat/Long and Mean Elevation

The AAR of the Chomolhari-Kulha Gangri Region plotted against latitude and longitude of this region illustrates that the Steady State of glaciers were well distributed throughout the lower latitudes with increasing longitudinal extend. Along with the Steady glaciers, Glaciers with Negative Mass Balance were also well distributed in the lower latitudes. On the other hand, maximum concentration of the Steady glaciers was in the lower longitudes having increasing latitudinal trend (Figure 3.19.). The glaciers with Positive State of Mass Balance were mostly concentrated in the mid-latitudes and were almost equally spread throughout the region.

Table 3.9: AAR Classwise Distribution of Glaciers of Chomolhari-Kulha Gangri Region		
	Class	**Frequency Of Glaciers**
Negative Mass Balance	< 0.5	145
Steady State	0.5 - 0.8	274
Positive Mass Balance	> 0.8	12
Source: Computed		

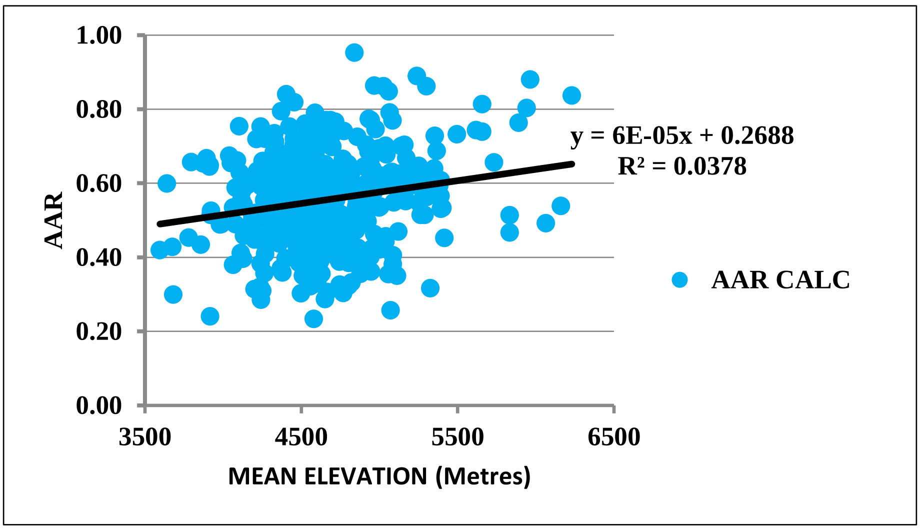
While on the other hand, AAR plotted against mean elevation for the Chomolhari-Kulha Gangri Region depict that the maximum glaciers were in Steady State (274) followed by glaciers with Negative Mass Balance (145) (Table 3.9.). Whereas the lowest frequency of glaciers had Positive Mass Balance (12). The glaciers with Positive Mass Balance followed the set pattern of high AAR values in high altitudinal areas (Figure 3.20.).

Figure 3.19: AAR of Chomolhari-Kulha Gangri Region Plotted Against Lat/Long



Source: Computed

Figure 3.20: AAR of Chomolhari-Kulha Gangri Region Plotted Against Mean



Source: Computed

Elevation wise Glacier Estimation

The huge east-west dimension of Bhutan has led to another sub-division of the region. Bhutan was thus divided into two hydrological divisions for this elevation-wise comparative study.

A. East Bhutan / Manas Chhu Basin

B. West Bhutan / Puna Tsang Chhu Basin (Alam et al., 2017)

The number of glaciers located at an elevation of <4000 m was the highest in east Bhutan (46.39%) while west Bhutan had 24.34% glaciers. In this elevation category, the accumulation area was high in east Bhutan 59.76%, whereas west Bhutan was not too far behind with 57.08% of the total glaciated area under accumulation. On the other hand, ablation area for east and west Bhutan in <4000 m elevation region was 40.15% and 42.81% respectively. The ablation area debris covered was quite high for both the east and west Bhutan i.e. 77.62% and 84.65% respectively in comparison to the ablation area ice-exposed.

This result points towards the stability of the glaciers. The glaciers are said to be more stable when the ablation area – ice-exposed is less than the ablation area – debris covered. According to Jackson & Fountain, 2007, glacier melt decreases in an exponential manner as the thickness of the debris layer increases.

The elevation category of 4000-5000 m comprises of the maximum number of glaciers i.e. 62.95% of the total 1158 glaciers in Bhutan. Reportedly, East Bhutan had 51.99% of glaciers while West Bhutan had almost twice the number of glaciers, i.e. 73.01% (Table 3.10. and Table 3.11.). But there was little difference between the glaciated areas of both regions compared to the overall glaciated area of Bhutan, where 27.19% of the area was under glaciers in the east and 35.75% in the western part of Bhutan. These statistics clearly points towards the fact that the glaciers in east Bhutan had a larger glacial area in comparison to the west Bhutan glaciers.

The ablation area in this elevation category, was less than the accumulated area. In east Bhutan the ablation area was 42.28% whereas it was 38.35% in west Bhutan. Indicating towards the good health of the glaciers. The ablation area – debris covered was again high in 4000-5000 m elevation category for both east and west Bhutan (76.89% and 87.24% respectively). Approximately 37 supra glacial lakes were reported in East Bhutan, accounting for 1.03% of the overall glacial area of the region. Whereas 35 supra glacial lakes in West Bhutan accounted for 0.40% of the total glacial area in this elevation zone. West Bhutan had one (1) moraine dammed lake accounting for an area of 7.38%.

Table 3.10: East Bhutan - Elevation Class-Wise Statistics

Sr. No.	Class	Glaciers (%)	Total Glaciated Area (%)	Accumulation Area (%)	Ablation Area (%)			Supra Glacial Lake		Moraine Dammed Lake	
					Debris	Ice Exposed	Total	No.	Area (%)	No.	Area (%)
1	< 4000	46.39	41.80	59.76	77.62	22.38	40.15	4	0.09	0	0.00
2	4000 – 5000	51.99	56.48	56.69	76.89	23.11	42.28	37	1.03	0	0.00
3	> 5000	1.62	1.72	60.66	100	0.00	39.24	1	0.09	0	0.00
	Total	**100**						**42**		**0**	

Source: Computed

Table 3.11: West Bhutan - Elevation Class-Wise Statistics

Sr. No.	Class	Glaciers (%)	Total Glaciated Area (%)	Accumulation Area (%)	Ablation Area (%)			Supra Glacial Lake		Moraine Dammed Lake	
					Debris	Ice Exposed	Total	No.	Area (%)	No.	Area (%)
1	< 4000	24.34	19.30	57.08	84.65	15.35	42.81	5	0.10	0	0
2	4000 – 5000	73.01	68.96	61.17	87.24	12.75	38.35	35	0.40	1	7.38
3	> 5000	2.65	11.72	78.86	10.80	89.20	19.64	3	0.80	2	92.62
	Total	**100**	**100**					**43**		**3**	

Source: Computed

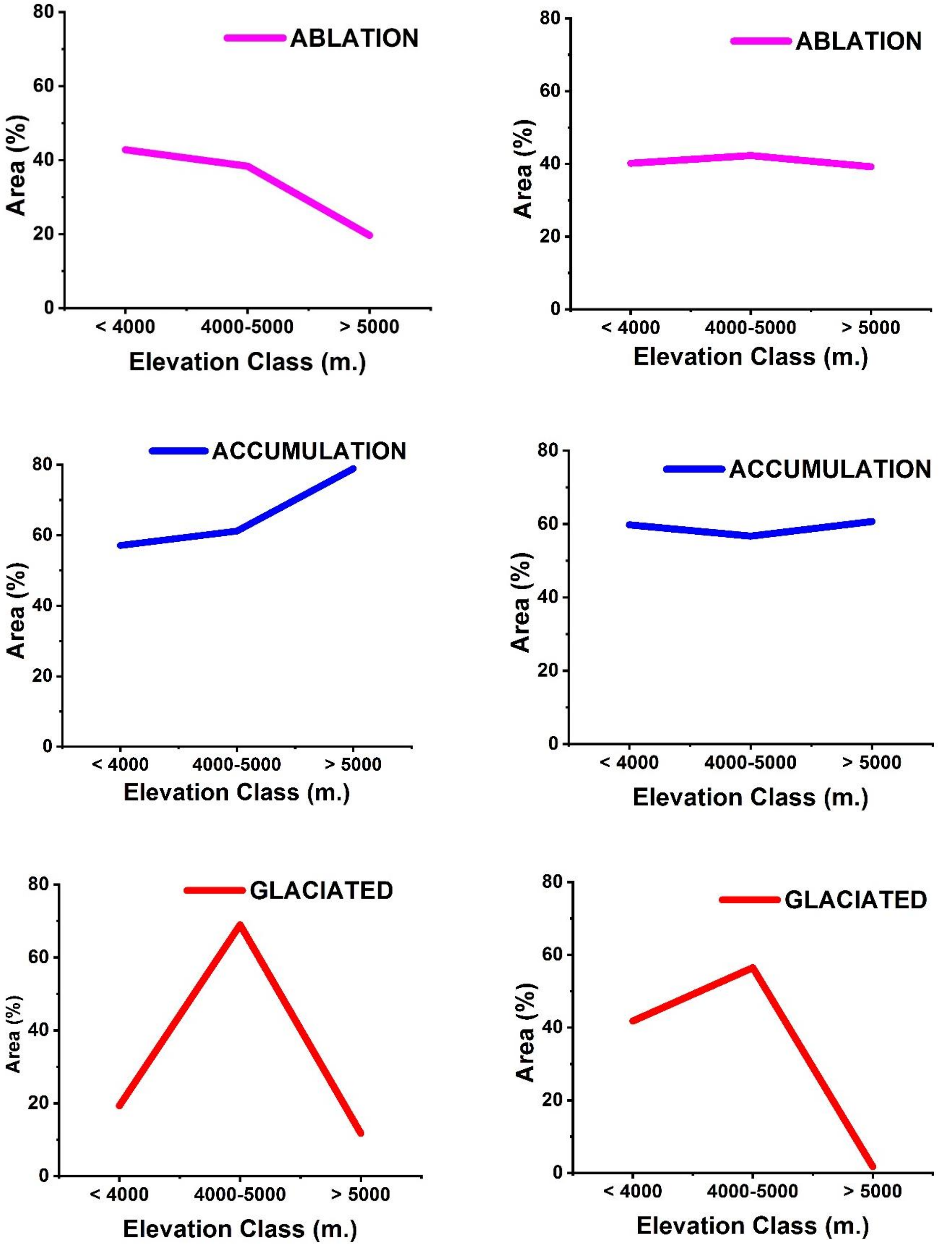
In >5000 metre elevation category 1.62% glaciers in east Bhutan and 2.65% glaciers in west Bhutan occupied a total of 1.72% and 11.72% glaciated areas respectively. Both east (60.66%) and west (78.66%) Bhutan had high accumulation area percentage. Approximately 39.24% area of the total glaciated area in east Bhutan was under ablation where the glaciers were devoid of ablation area – ice-exposed and were only covered with debris (Table 3.10.). All this indicates, that the glaciers which were located in this region were large compound glaciers having low melt rate pertaining to low exposure to sunlight. Whereas, the west Bhutan region (Table 3.11) had only 10.80% area under ablation area – debris cover while 89.20% glacial area in the ablation region was ice exposed i.e. more prone to melting.

There were three (3) supra glacial lakes in west Bhutan in the >5000 metre elevation category occupying an area of 0.79% of the total glaciated area in this elevation category. On the other hand, west Bhutan had two (2) supra glacial lakes in the >5000 metre elevation category covering an area of about 0.73% only of the total glaciated region. The statistics thus generated gives a clear picture of the conditions of the glaciers of that region. Seeing the results, the inferences that have been made suggest that optimal conditions have been met, thereby leading to the formation of these moraine dammed lakes. To name a handful, massive quantities of debris supply and less melting water to carry these sediments far are some of the favorable circumstances (Benn et. al., 2001 and Hambrey et al., 2008).

Figure 3.21 (Bajpai and Kanchan, 2021) representing the class wise distribution gives a better picture for total glaciated area, accumulation area and the ablation areas for both the regions of east and west Bhutan. On the other hand Figure 3.22 gives a good representation of the different glacier features in the form of Glacier inventory map of Bhutan. Whereas, Figure 3.23 gives a total representation of the glaciers of the total Bhutan sub-basin.

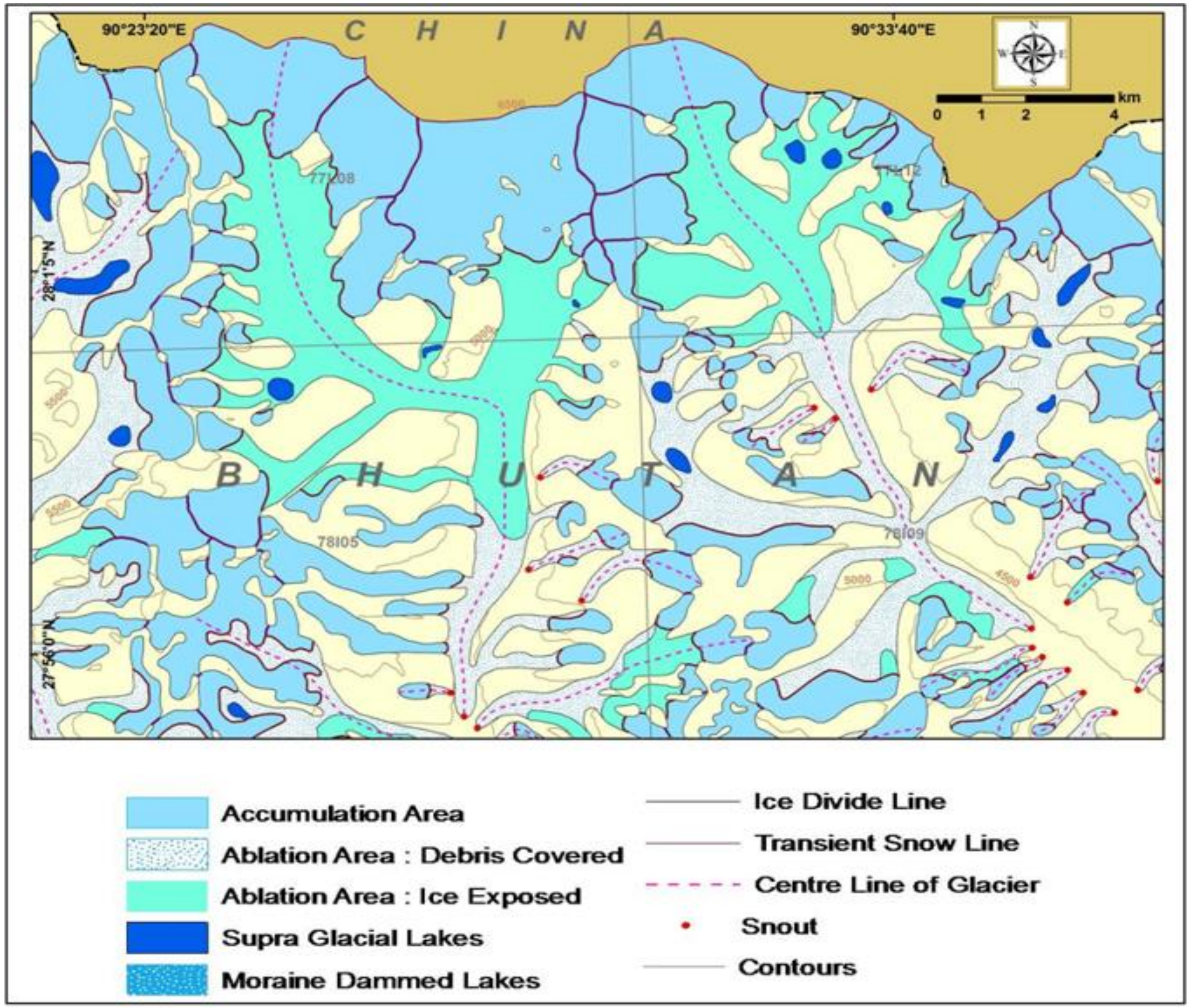
Figure 3.21: Bhutan - Elevation Class wise distribution of Total Glaciated, Accumulation and Ablation area

West Bhutan | **East Bhutan**



Source: Computed

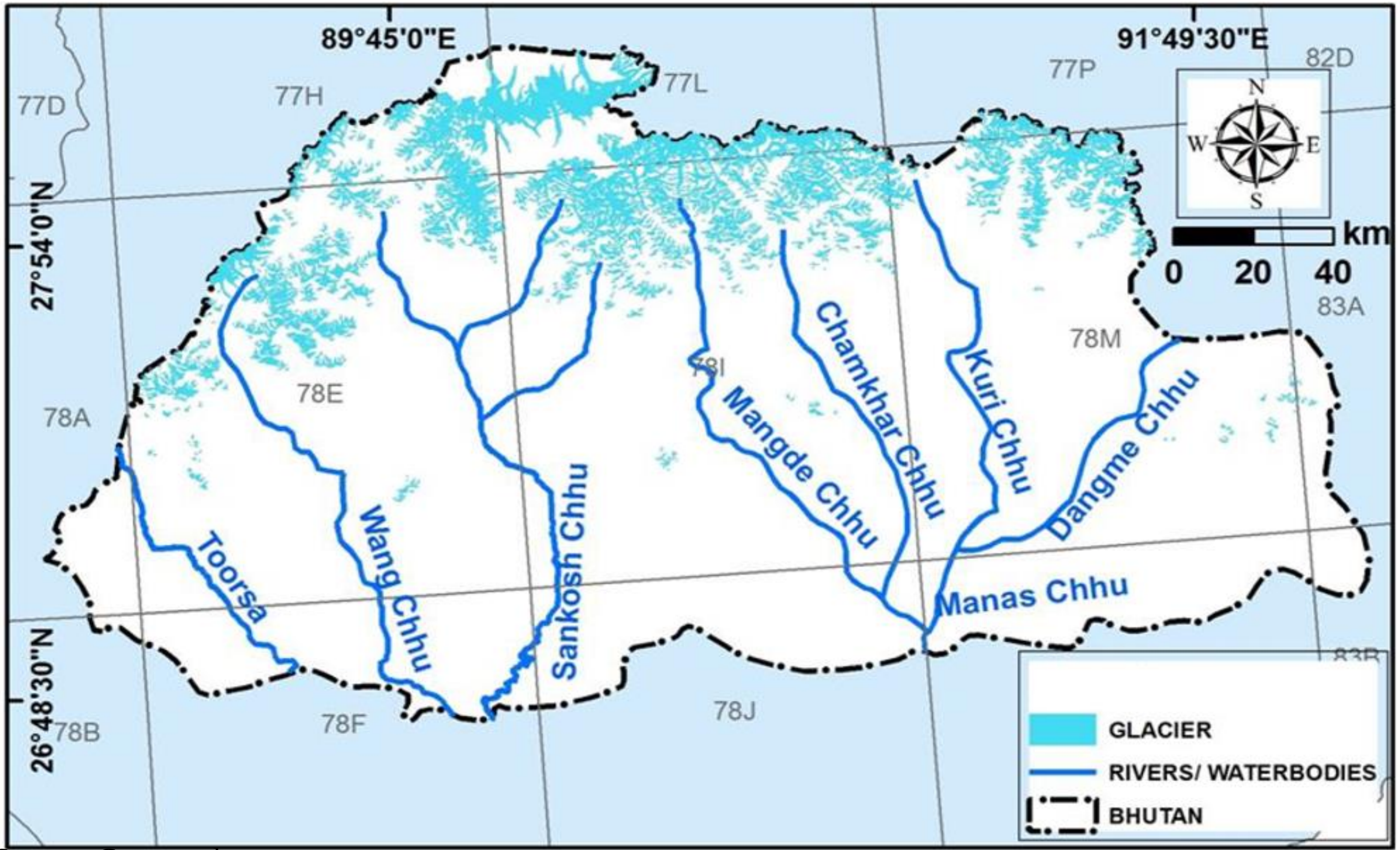
Figure 3.22: Glacier Inventory Map of Bhutan



Note: This Figure represents the Final Glacier Inventory Map of Bhutan elucidating all the point, line and polygon features mapped.

Source: Computed

Figure 3.23: Glaciated Region of Bhutan Sub-Basin



Source: Computed

Resume

This chapter discusses the "Glacier Inventory" aspect of the thesis. It begins with how distinct glacier features are identified on satellite data then progresses to glacial estimations and computations for the two Eastern Himalayan locations under investigation viz., Sikkim and Bhutan. The next chapter examines the Hazard Zonation Mapping of Moraine Dammed Lakes.