Published Papers

ANNALs, NAGI VOLUME 41 (NO. 2), DECEMBER 2021, Page 255–270

ELEVATION BASED COMPARATIVE ANALYSIS OF GLACIERS OF SIKKIM AND BHUTAN USING REMOTE SENSING DATA

VANYA BAJPAI AND ROLEE KANCHAN[1]

ABSTRACT

Information of the distribution and features of glaciers in the Himalayan Mountains is still inadequate and heterogeneous. These glaciers have recently become significant as these are being used as climate change indicators. As a consequence, maintaining a database in the form of Digital Glacier Inventories of these solid freshwater resources has become crucial.

Hypsometric relationships are important as they give an insight into the vulnerability of glaciers to climate change. This paper makes an attempt to study the trends of glacier area, glacier number and changes in glaciers according to altitude in Sikkim (India) and Bhutan. As optimal circumstances for glacier growth exist, an increase in the number of glaciers or their size is assumed to be closely linked to an increase in the altitude. Glaciers of this areas were thus inventoried by remote sensing methods using IRS LISS III, AWiFS and SRTM DEM data in the Geographic Information System (GIS) setting.

As testified by several scholars (Bolch, et al., 2012) the investigation of glaciers of Sikkim and Bhutan also showed that, the highest concentration of glaciers is in the 4000-5000 m. elevation class. Bhutan had the maximum glacial region (62.95%) in the same category, i.e. 4000-5000 m. Whereas Sikkim, at the elevation of > 4000 m. had the largest concentration of glacial area (60.56%), thus rendering the theory partly correct. Although the number of glaciers and the area covered (6.91%) were the lowest in Bhutan's > 5000 m. elevation region, but the average glacier size (13 km) was very high. Finally, it

1. Department of Geography, Faculty of Science, The Maharaja Sayajirao University of Baroda, Vadodara, Gujarat, India.
Email: roleekanchan@gmail.com

Received on 10.05.2021 Accepted on 24.06.2021

DOI: https://doi.org/10.32381/ATNAGI.2021.41.02.3

was observed that the average glacier size in both the study areas was the lowest in the < 4000 m. elevation class.

Keywords: *Glacier area, Glacier number, Glacier altitude, Accumulation, Ablation, Supra glacial lakes, Moraine dammed lakes.*

INTRODUCTION

Glaciers act as repositories of information for various climate change studies. Due to their possible influence on the water balance of a particular region glaciers have recently emerged as critical drivers of the earth's ecosystem (Beniston, 2003). Melting of the glaciers have become a major concern in today's time. This not only reduces the glacier area but also increases the number of glaciers due to their fragmentation (Bajracharya *et al.*, 2006 a, b, 2007 a, b, 2008, 2009 a). Monitoring of these high altitude glaciers is the need of the hour, to which the remote sensing approach exhibits as the best way of monitoring them in detail. These digital glacier datasets are priceless data stores as they provide quick and exact findings in emergency circumstances such as natural catastrophes. This paper seeks to analyze the glaciers of Bhutan (East & West) and Sikkim considering elevation groups of < 4000 m., 4000-5000 m., and > 5000 m. Variations in glacier features are associated with elevation changes (Paterson, 1994). Thus, an elevation-based comparative investigation was conducted to evaluate glacier variations as a function of varying altitudes, as well as to get a better understanding of how altitude affects glacial melt and retreat. Thus in this process, essential glacial characteristics would be investigated and assessed taking their altitudinal distribution into consideration. Furthermore, the relationship between glacier size and glacier height would also be reviewed.

STUDY AREA

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

Bhutan: The kingdom of Bhutan extending between 27° to 29° north latitudes and 89° to 92° east longitudes is a small landlocked country. Its rugged terrain is surrounded by the Tibetan Region to the north and bordered by the Indian states of West Bengal, Sikkim, Assam and Arunachal Pradesh to the east, west and south respectively. With a geographical area of 40210.63 sq. km. Bhutan extends 320 km. east-west and 150 km. north-south. The geomorphic regime of the state is quite undulating; the northern part has the lofty ranges of the Great Himalayas while to the north-west Chomolhari range marks a frontier with the Chumbi valley of Tibet. Seven drainage systems flowing southwards incise through the six major mountain ranges of Bhutan running north to south, roughly parallel to each other. Listing from west to east the rivers which join the mighty Brahmaputra in Assam are: Torsa, Wang Chu, Sankosh, Mangdi Chu, Bumthang Chu, Kuru Chu, and Kulong Chu (Fraser *et al.*, 2001) (Figure 1). As the horizontal extent of Bhutan is too much thus for the present study Bhutan was divided into east and west parts on the basis of the river basins.

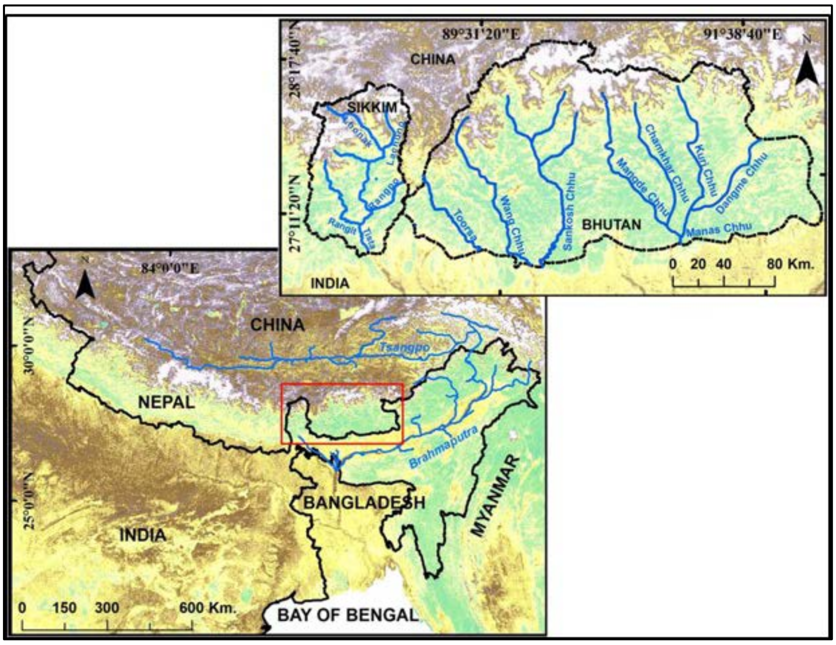


Fig. 1: Study Area Location Map

MATERIALS AND METHODS

Methodology

Satellite Data used

Geocoded cloud-free 23.5 m. resolution data of IRS LISS-III (Indian Remote Sensing Satellite, Linear Imaging Self Scanning-III) and 56 m. resolution AWiFS (Advanced Wide Field Sensor) scenes from July to

September, i.e. end of ablation season for the years 2006-2008 with minimal snow cover were obtained from National Remote Sensing Centre (NRSC), Hyderabad – ISRO (Indian Space Research Organization). The spectral bands of AWiFS and LISS-III are similar, thus theFalse Colour Composites (FCC's) of standard band combinations of Band 2 (0.52-0.59 μm), Band 3 (0.62-0.68 μm), Band 4 (0.77-0.86 μm) and Short Wave Infrared (SWIR) band (1.55-1.70 μm) of both the satellite data were used for the present work. 30-m gridded Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) was used to derive the elevation information for each glacier, to compute the elevation trends (SAC, 2011) (Figure 2).

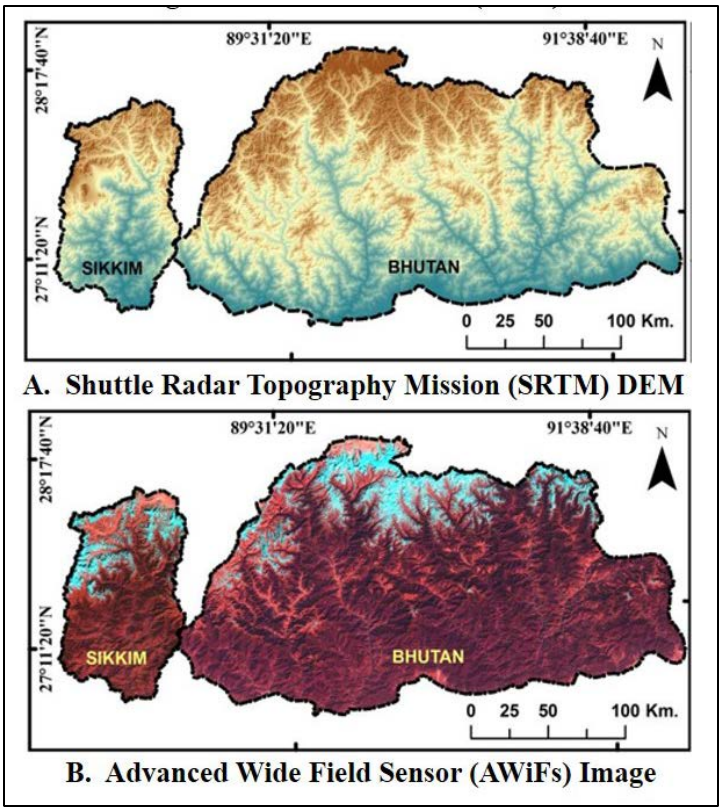


Fig. 2: Satellite datasets (A & B)

Datasets used for Base map preparation:

An inventory for each glacier at 1:50,000 scale was created in a well-defined format suggested by United Nations Temporary Technical Secretariat (UNESCO/TTS) (Müller, *et al.*, 1977) also containing information related to the glacial lakes. Preparation and assimilation of these primary layers was carried out in GIS (ArcMap 10.2) through visual interpretation and these layers were grouped into categories –Firstly, Survey of India (SOI) and Survey of Bhutan (SOB) topographical maps at 1:50,000 scale, guide maps, trekking routes and political maps were used to create the base map information for defining the research area's political boundary. Secondly, the Hydrological and geological Information like defining the basin boundaries, identifying mountain ranges along with the network of streams and rivers flowing in the basin was done using the Drainage maps from the Irrigation Atlas of India (National Atlas Organization, 1972) and Natural resources atlas of Sikkim (Nag, 2006), Basin boundary maps other physiographic maps from Land Use Survey, Watershed Atlas of All India (Soil, 1990) (AIS & LUS) and the Zonation of Bhutan done by Norbu (Norbu, 2003).

Glacier and De-glaciated valley features (Sharma *et al*., 2008) were firstly verified using the available Snow and Glacier maps (at 1:250,000) (Bahuguna *et al*., 2001 and Kulkarni *et al*., 2005) were referred for identification of already mapped glacial data.

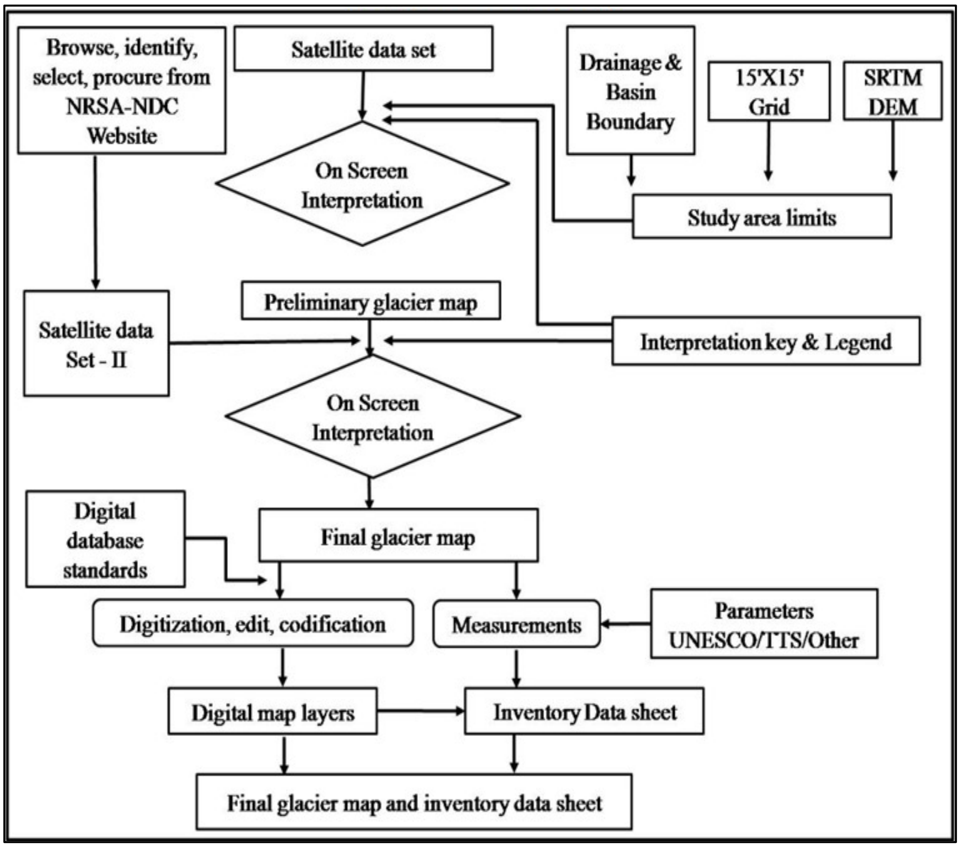


Fig. 3: Broad approach followed for Glacier Mapping (Bajpai *et al*., 2016)

On screen visual interpretation was carried out for mapping and delineation of the glaciers and their morphological features. The first set of satellite data was used for mapping all the glacial features. For any gap areas or in case of non-availability of cloud free data the second set of satellite data was referred. Thus, for the preparation of final datasheet in GIS environment, for each glacial feature systematic observations were made and their areas were recorded in a tabular format which was then linked via unique glacier identification number to the corresponding glacier. The approach followed in the present work was depicted in the flowchart (Figure 3).

RESULTS AND DISCUSSION

Sikkim: The statistics generated from the present study report that the state of Sikkim that corresponds to the Tista sub-basin had 1321.41 sq. km. under 394 glaciers (Bajpai *et al.*, 2014). In the elevation classes of < 4000 m. and > 5000 m. debris covered area (90.27% and 66.61% respectively) was more than the ice-exposed region (9.72% and 33.10% respectively). On the other hand, in 4000-5000 m. elevation class ablation area ice exposed (55.60%) was higher 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.

As given in Table1 the total accumulation area was the least (53.32%) in the < 4000 m. elevation category, in comparison to other elevation categories of 4000-5000 m. (61.14%) and > 5000 m. (64.13%). The total area under ablation in > 5000 m. class was 35.87% followed by the elevation class of 4000-5000 m. (38.86%) and < 4000 m. (46.68%).

Table 1: Sikkim-Elevation Class-wise statistics

Sr. No.	Class	Total Glaciers	Total Glaciated Area (%)	Accum-ulation Area (%)	Ablation Area (%)			Supra Glacial Lake		Moraine Dammed Lake	
					Debris	Ice Exposed	Total	No.	Area (%)	No.	Area (%)
1	<4000	22	1.77	53.32	90.27	9.72	46.68	0	0	0	0
2	4000-5000	247	37.67	61.14	44.4	55.6	69.9	16	0.21	0	0
3	>5000	125	60.56	64.13	66.61	33.1	35.87	47	1.22	2	0.36
Total		394	100					63		2	

Source: Computed

These statistics indicate towards the fact that glaciers located in the elevation class of > 5000 m. have higher accumulation area and less ablation area as precipitation exceeds the glacier melt (Ali, *et al*., 2015). In the < 4000 m. elevation category the accumulation zone and ablation zone 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 4). 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 few supra glacial lakes (SGL) (16) in the 4000-5000 m. elevation glacier category having an area of about 0.21% of the total glaciated area, while in the elevation category of > 5000 m. approximately 1.22% area of the total glaciated region of this category was occupied by 47 supra glacial lakes. On the other hand there was no record of Moraine Dammed lakes in other elevation classes except in the > 5000 m. category where an area of about 0.36% of the total glaciated area was occupied by 2 large lakes.

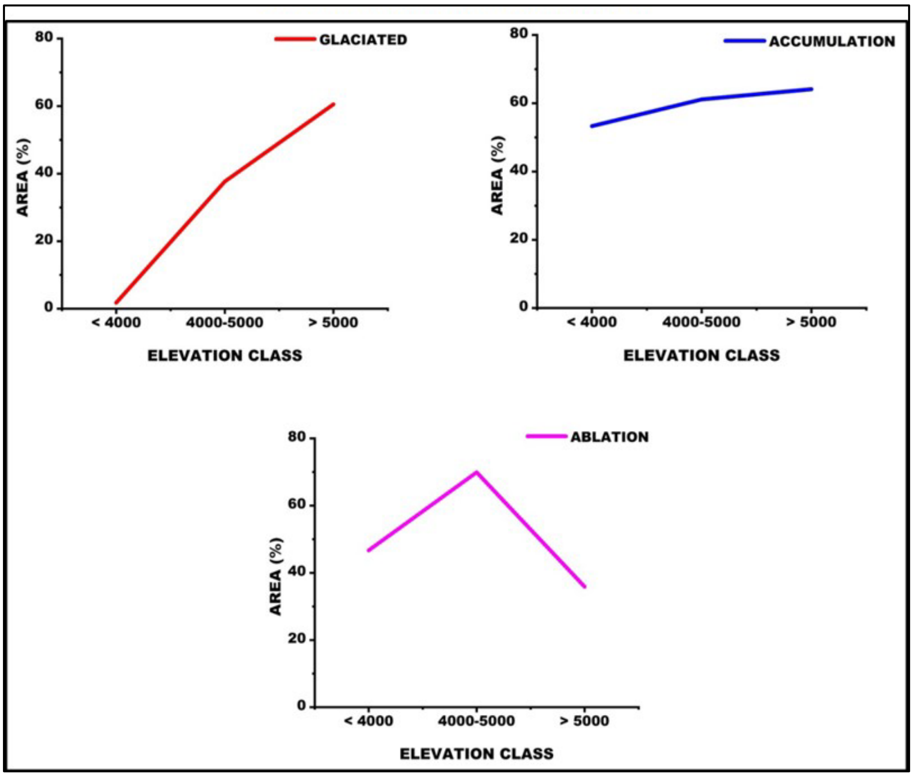


Fig. 4: Elevation Class wise distribution of Total Glaciated, Accumulation and Ablation area

Figure 5 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. Whereas Figure 6 shows the total glaciated area of Sikkim and therefore the Tistariver and its tributaries.

Bhutan: As discussed earlier, because of its huge east-west dimension, Bhutan was 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)

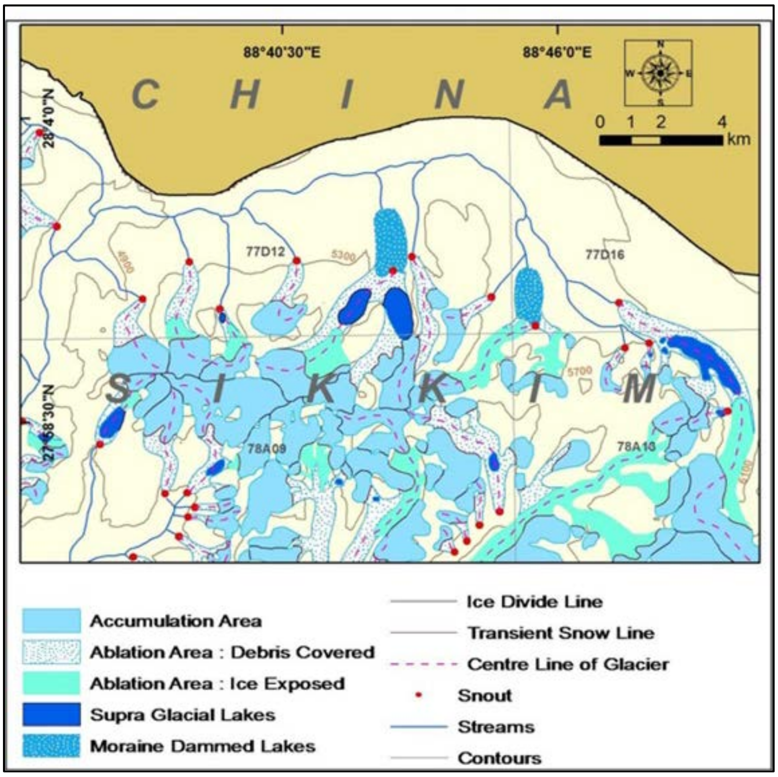


Fig. 5: Glacier inventory Map of Sikkim (Tista sub-basin)

The number of glaciers located at an elevation of < 4000 m. was the highest in east Bhutan (257) while west Bhutan had 147 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.

Fig. 6: Glaciated region of Sikkim (Tista sub-basin)

This finding relates to a fact that indicates glacier stability. When the ablation area – ice-exposed is less than the ablation area – debris-covered, the glaciers are considered to be more stable. (Østrem, 1975; Fujii, 1977; Mattson, 1993). 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 288 of glaciers while West Bhutan has almost twice the number of glaciers, i.e. 441 (Table 2 and Table 3). 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.

Table 2: East Bhutan-Elevation Class-wise statistics

Sr. No.	Class	Total Glaciers	Total Glaciated Area (%)	Accumulation Area (%)	Ablation Area (%)			Supra Glacial Lake		Moraine Dammed Lake	
					Debris	Ice Exposed	Total	No.	Area (%)	No.	Area (%)
1	<4000	257	41.8	59.76	77.62	22.38	40.15	4	0.09	0	0
2	4000-5000	288	56.48	56.69	76.89	23.11	42.28	37	1.03	0	0
3	>5000	9	1.72	60.66	100	0	39.24	1	0.09	0	0
Total		554	100	100				42			

Source: Computed

Table 3: West Bhutan-Elevation Class-wise statistics

Sr. No.	Class	Total Glaciers	Total Glaciated Area (%)	Accumulation Area (%)	Ablation Area (%)			Supra Glacial Lake		Moraine Dammed Lake	
					Debris	Ice Exposed	Total	No.	Area (%)	No.	Area (%)
1	<4000	147	19.3	57.08	84.65	15.35	42.81	5	0.1	0	0
2	4000-5000	441	68.96	61.17	87.24	12.75	38.35	35	0.4	1	7.38
3	>5000	16	11.72	78.86	10.8	89.20	19.64	3	0.8	2	92.62
Total		378	100					10			

Source: Computed

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 1 moraine dammed lake accounting for an area of 7.38%.

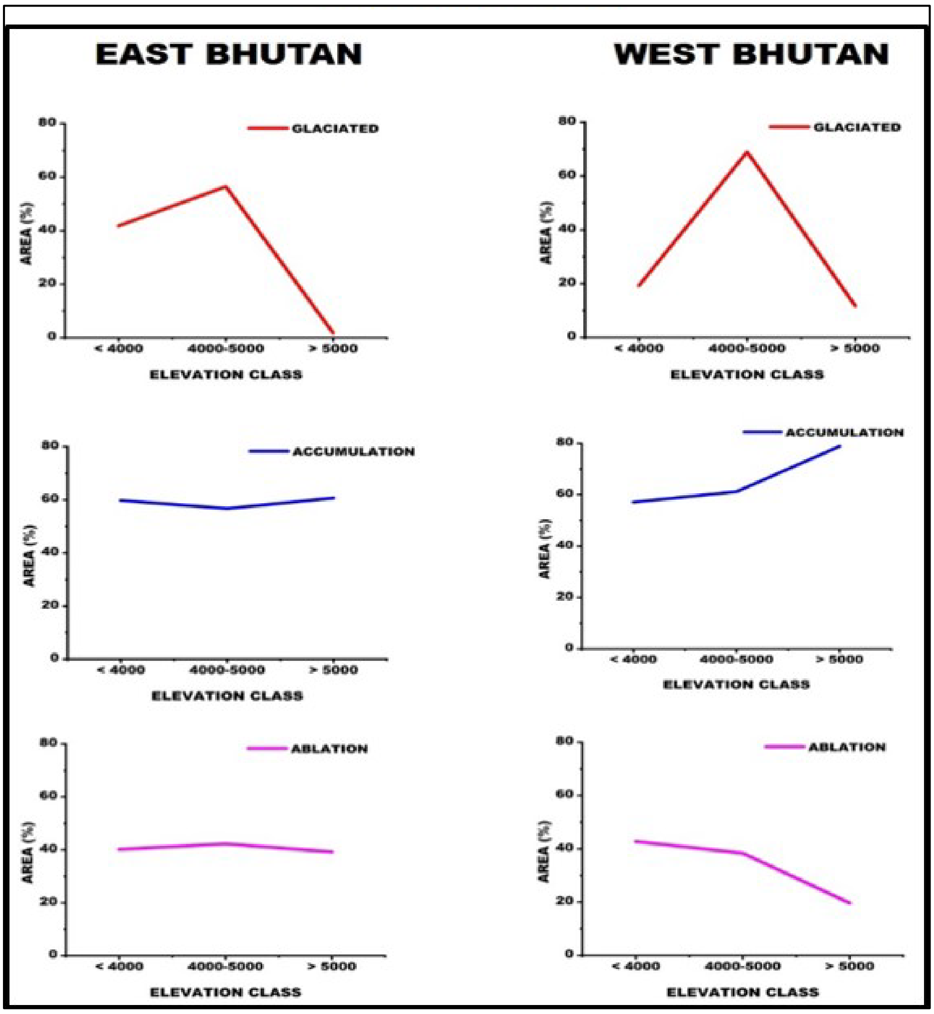


Fig. 7: Bhutan-Elevation Class wise distribution of Total Glaciated, Accumulation and Ablation area

In > 5000 m. elevation category 9 glaciers in east Bhutan and 16 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 (2). 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) 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 3 supra glacial lakes in west Bhutan in the > 5000 m. elevation category occupying an area of 0.79% of the total glaciated are in this elevation category. On the other hand, only west Bhutan had supra glacial lakes (2) in the > 5000 m. elevation category covering an area of about 0.73% 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

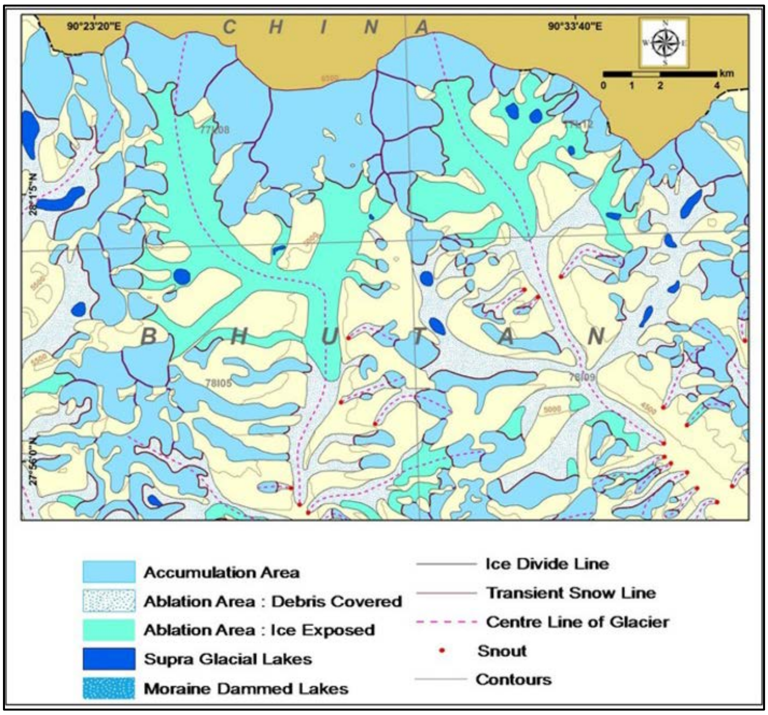


Fig. 8: Glacier inventory Map of Bhutan

sediments far are some of the favorable circumstances. (Benn *et al*., 2001 and Hambrey *et al*., 2008).

Figure 7 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 8 gives a good representation of the different glacier features in the form of Glacier inventory map of Bhutan. Whereas, Figure 9 gives a total representation of the glaciers of the total Bhutan sub-basin.

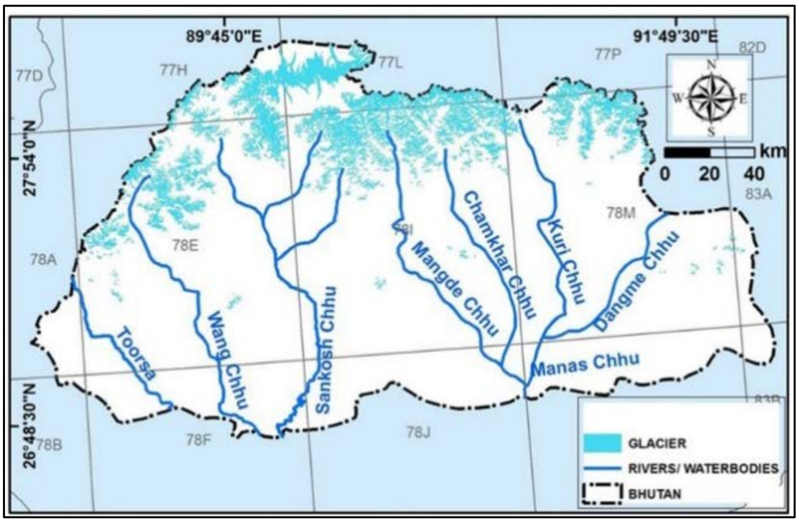


Fig. 9: Glaciated region of Bhutan sub-basin

CONCLUSION

In the present study we tried to analyze the various components of the glaciers of Sikkim and Bhutan in an elevation wise scenario. Analysing a total of 1552 glaciers without any sub-division or classification would not have done justice to the study. Therefore, glaciers were categorized into 3 elevation classes, i.e. < 4000 m., 4000-5000 m., and > 5000 m.

Hence the statistics reveal that Bhutan had the largest glacial concentration in 4000-5000 m. elevation category, i.e. 60.56% of the total glaciated area. While with 125 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 both Sikkim (247) and Bhutan (729). Thus, more than 60% of the total glacial concentration of both the regions, i.e. Sikkim and Bhutan was observed in 4000-5000 m. elevation category.

While, Bhutan on the other hand, attributed for the lowest number of glaciers (19) and also the lowest total area covered (6.91%) in > 5000 m. elevation category, but the average glacial size was the highest (13 km.). It was also noted that the average glacier size in both 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. Figure 10 is a Hypsometric graph showing the total area (percent) and altitude (percent) of Bhutan (East & West) and Sikkim glaciers. It can be observed that the maximum glacial area was recorded in the 4000-5000 m. elevation class in Bhutan. Whereas Sikkim had the highest glacial area in the > 5000 m. elevation group.

REFERENCES

Alam, F., Alam, Q., Reza, S., Khurshid-ul-Alam, S. M., Saleque, K., & Chowdhury, H. (2017). Sourcing green power in Bhutan: A review. *Energy Procedia.* 110: 586-591.

Ali, S., Li, D., Congbin, F., & Khan, F. (2015). Twenty first century climatic and hydrological changes over Upper Indus Basin of Himalayan region of Pakistan. *Environmental Research Letters*. 10(1): 014007.

Bahuguna, I.M., Kulkarni, A.V., Arrawatia, M.L. and Shresta, D.G. (2001). Glacier Atlas of Tista basin (Sikkim Himalayas). SAC/RESA/MWRGGLI/SN/16, Ahmedabad, India.

Bajpai, V., Kanchan R., Bahuguna, I.M. (2016). Geospatial Technique Based Glacial Inventory of Bhutan Himalayas, Bhutan. *International Research Journal of Environment Sciences.* 5(9): 32-39.

Bajpai, V., Kanchan R., Sharma, A. K. (2014). Remote Sensing and GIS based Glacier Inventory: A Case Study of Tista Sub-Basin, Brahmaputra River Basin. *Deccan Geographer* (Vol. 53, No. 1, pp. 29-37).

Bajracharya, S. R., & Mool, P. (2009a). Glaciers, glacial lakes and glacial lake outburst floods in the Mount Everest region, Nepal. *Annals of Glaciology*. 50(53): 81-86.

Bajracharya, S. R., Mool, P. K., & Shrestha, B. R. (2008). Global climate change and melting of Himalayan glaciers. Melting glaciers and rising sea levels: Impacts and implications, 28-46.

Bajracharya, S. R., Mool, P. K., & Shrestha, B. R. (2007a). Impact of climate change on Himalayan glaciers and glacial lakes: case studies on GLOF and associated hazards in Nepal and Bhutan. International Centre for Integrated Mountain Development (ICIMOD).

Bajracharya, S. R., & Mool, P.K. (2007b). Melting glaciers in the Himalaya. *In Mountain Forum Bulletin* (Vol. 7, No. 2, pp. 5-6).

Bajracharya, S. R., Mool, P. K., & Shrestha, B. R. (2006a, November). The impact of global warming on the glaciers of the Himalaya. In Proceedings of the International Symposium on Geodisasters, Infrastructure Management and Protection of World Heritage Sites (pp. 231-242).

Bajracharya, S. R., & Mool, P. K. (2006b). Impact of global climate change from 1970s to 2000s on the glaciers and glacial lakes in Tamor Basin, eastern Nepal. Unpublished report for ICIMOD, Kathmandu.

Beniston, M. (2003). Climatic change in mountain regions: a review of possible impacts. Climate variability and change in high elevation regions: Past, present & future, 5-31.

Bolch, T., Kulkarni, A., Kääb, A., Huggel, C., Paul, F., Cogley, J. G., ...& Stoffel, M. (2012). The state and fate of Himalayan glaciers. *Science*. 336(6079): 310-314.

Fujii, Y. (1977). Field Experiment on Glacier Ablation under a Layer of Debris Cover Glaciological Expedition of Nepal, Contribution No. 33. *Journal of the Japanese Society of Snow and Ice,* 39(Special), 20-21.

Fraser, N., Bhattacharya, A., & Bhattacharya, B. (2001). Geography of a Himalayan kingdom: Bhutan. Concept Publishing Company.

Karan, P. P., & Jenkins, W. M. (1963). The Himalayan Kingdoms: Bhutan, Sikkim, and Nepal.

Kulkarni, A.V., Rathore, B. P., Mahajan, S. and Mathur, P. (2005). Alarming retreat of Parbati Glacier, Beas basin, Himachal Pradesh. *Current Science*. 88(11): 1844-1850.

Mattson, L. E. (1993). Ablation on debris covered glaciers: an example from the Rakhiot Glacier, Punjab, Himalaya. *Intern. Assoc. Hydrol. Sci.* 218: 289-296.

Müller, F., Caflisch, T., & Müller, G. (1977). Instructions for compilation and assemblage of data for a World Glacier Inventory. Zurich: Department of Geography, Swiss Federal Institute of Technology (ETH). National Atlas Organization (1972). Irrigation Atlas of India. Calcutta: National Atlas Organization.

Nag, P. (2006). Natural resources atlas of Sikkim. National Atlas & Thematic Mapping Organisation, Department of Science & Technology, Government of India.

Norbu, C. (2003). A provisional physiographic zonation of Bhutan.

Østrem, G. (1975). ERTS data in glaciology— An effort to monitor glacier mass balance from satellite imagery. *Journal of Glaciology*. 15(73): 403-415.

Paterson, W. S. B. (1994). Physics of glaciers. Butterworth-Heinemann.

SAC (2011). Snow and Glaciers of the Himalayas (Study carried out under the joint project of Ministry of Environment and Forests and Department of Space, Government of India), Space Applications Centre, ISRO, Ahmedabad, India ISBN 13, 978-81-909978-7-4.

Sharma, A. K., Singh, S., & Kulkarni, A. V. (2008). Approach for Himalayan Glacier Inventory using remote sensing and GIS techniques. In Proceedings of International Workshop on Snow, Ice, Glacier and Avalanches. IIT-B. Tata McGraw-Hill Publishing Company Ltd, New Delhi, pp. 177-185.

Soil, A. I. (1990). Land Use Survey, Watershed atlas of India (on 1: 1 million scale). Department of Agriculture and Cooperation, Government of India, IARI Campus, New Delhi.

http://www.sikenvis.nic.in/Database/NaturalResources_790.aspx?format=Print, accessed on 15 September, 2020

http://www.kingdomofbhutan.com/kingdom/kingdom_1.html, accessed on 15 September, 2020

International Research Journal of Environment Sciences E-ISSN 2319–1414
Vol. 5(9), 1-5, September (2016) Int. Res. J. Environment Sci.

Geospatial Technique Based Glacial Inventory of Bhutan Himalayas, Bhutan

Vanya Bajpai[1], Rolee Kanchan[1]* I.M. Bahuguna[2]
[1]Department of Geography, Faculty of Science, The Maharaja Sayajirao University of Baroda, Vadodara, Gujarat, India
[2]Space Applications Centre, Indian Space Research Organization, Ahmedabad 380 015, India
roleekanchan@gmail.com

Available online at: www.isca.in, www.isca.me
Received 30th June 2016, revised 30th August 2016, accepted 11th September 2016

Abstract

The glaciers of the Himalayan region have gained a lot of importance in the recent past as they play an active role in climate change. Keeping an account of the glaciers, which are considered as the store house of solid fresh water has become essential as they actively contribute to the perennial rivers of the country. This task of monitoring and delineating the glaciers of Bhutan Himalayas was therefore implemented by IRS LISS III, AWiFS and SRTM DEM data using Geographic Information System (GIS). The focus of the present study was towards inventorying the glaciers of Bhutan Himalayas and statistically analyzing the results of the various glacial parameters. It was inferred that, out of the total glaciated parts of the Brahmaputra Basin, 17.97% volume of ice was trapped in the glaciers of Bhutan sub-basin. The glaciers were further sub-divided into smaller units and classified into three physiographic divisions. This categorization helped in the better understanding of the glacier behavior according to the size - number ratio giving an important result that, maximum number (432) of glaciers with largest glacier size (50 sq. km. to 121 sq. km) were concentrated in the Chomolhari-Kulha Gangri region which is a part of the Greater Himalayas.

Keywords: Accumulation, Ablation, Orientation.

Introduction

The Himalayan Mountain range was sometimes termed as the "Third pole", as it equaled the icy cold conditions that existed in the Polar regions[1] and also had the largest agglomeration of snow and glaciers out of the two poles. Nowadays the Himalayan region has become a global hotspot for hydropower development and environmental management for the future. These glaciers which are a unique reservoir for water storage[2] not only enrich the rivers of the young fold mountains through their melt waters but they also provide direct source of information on climate change[3]. For that reason, studying their evolution becomes an important issue as glacier melt may significantly contribute to ongoing rise in sea level[4]. Therefore, a systematic, reliable and scientific health assessment of these glaciers is the need of the hour.

The initial step towards forecasting the future water resources of this area were to measure the ongoing glacier depletion[5]. This calculation was possible using certain climate series indicators (temperature and precipitation), but incase of the unavailability of this kind of data, use of certain other indicators like mass balance, changes in glacier length or areal extent will help to forecast the stored glacial resources[6,7].

Till the recent past the Himalayan glaciers were poorly sampled on the field because of the use of manual methods. With the advent of remote sensing techniques in glacial studies, extensive glacier mapping with utmost accuracy was possible[8-10]. Many government and private organizations along with large number of scientists throughout the world are working towards mapping the glaciers of the Eastern Himalayan region.

Thus, this present work aims to make a small contribution towards the glacier community by inventorying these glaciers and related features for the Bhutan Himalayas.

Materials and Methods

Study area: The area under study i.e. the Kingdom of Bhutan stretches between 27°N to 29°N latitude and 89°E to 92°E longitude with an aerial coverage of about 40210.63 sq. km. in the Eastern Himalayan region.

This small land-locked country with an east-west extent of 320 km. and a north-south coverage of 150 km. (Figure-1) is geopolitically quite significant as it shares the international boundaries with China (Tibet) in the north and northeast and with the Indian sub-continent (between Assam-Bengal plains) in the east, west and south. Geomorphologically, the topography of the study area is quite sketchy, from the subtropical plains in the south to the sub alpine snow capped ranges in the north attaining heights of more than 7500 m.[11].

Regional sub-divisions made by R.L. Singh[12] were thus accepted and considered for the current study where the focus was on the three glaciated physiographic units. i. The Chomolhari-Kulha Gangri region (North), ii. The Trongsa region (West), iii. The Punakha-Thimphu region (East)

Methodology: Datasets used for Glacier Mapping: For the present study, Geocoded Indian Remote Sensing satellite datasets for the years 2006-2008 were referred for the end of ablation season which was from July to September. False Colour Composites (FCC's) of standard band combinations of Band 2 (0.52-0.59 µm), Band 3 (0.62-0.68 µm), Band 4 (0.77-0.86 µm) and Short Wave Infrared (SWIR) band (1.55-1.70 µm) of Linear Imaging Self Scanning (LISS) III and Advanced Wide Field Sensor (AWiFs) were used. Most of the mapping part was completed using the LISS III dataset but for some gap areas AWiFs data was also referred.

Inventory data of Bhutan sub-basin was created for each glacier in a well defined format with 37 parameters recommended by United Nations Temporary Technical Secretariat (UNESCO/TTS)[13] which also included elevation information, which was sought from the Digital Elevation Model (DEM) generated from the Shuttle Radar Topography Mission (SRTM) (Figure-2). Later 11 additional parameters were incorporated which contained information related to the glacial lakes.

Datasets used for Base map preparation: Collateral data such as Survey of Bhutan (SOB) topographical maps at 1:50,000 scale, trekking routes, guide maps, political maps were referred for the delineation of political boundary to define the study area. Drainage maps[14], Basin boundary maps from the Department of Survey and Land Records[15] were used to define the basin boundary and identify mountain ranges along with the network of streams and rivers flowing in the basin. Available Snow and Glacier maps (at 1:250,000)[16,17] were referred for identification of already mapped glacial data.

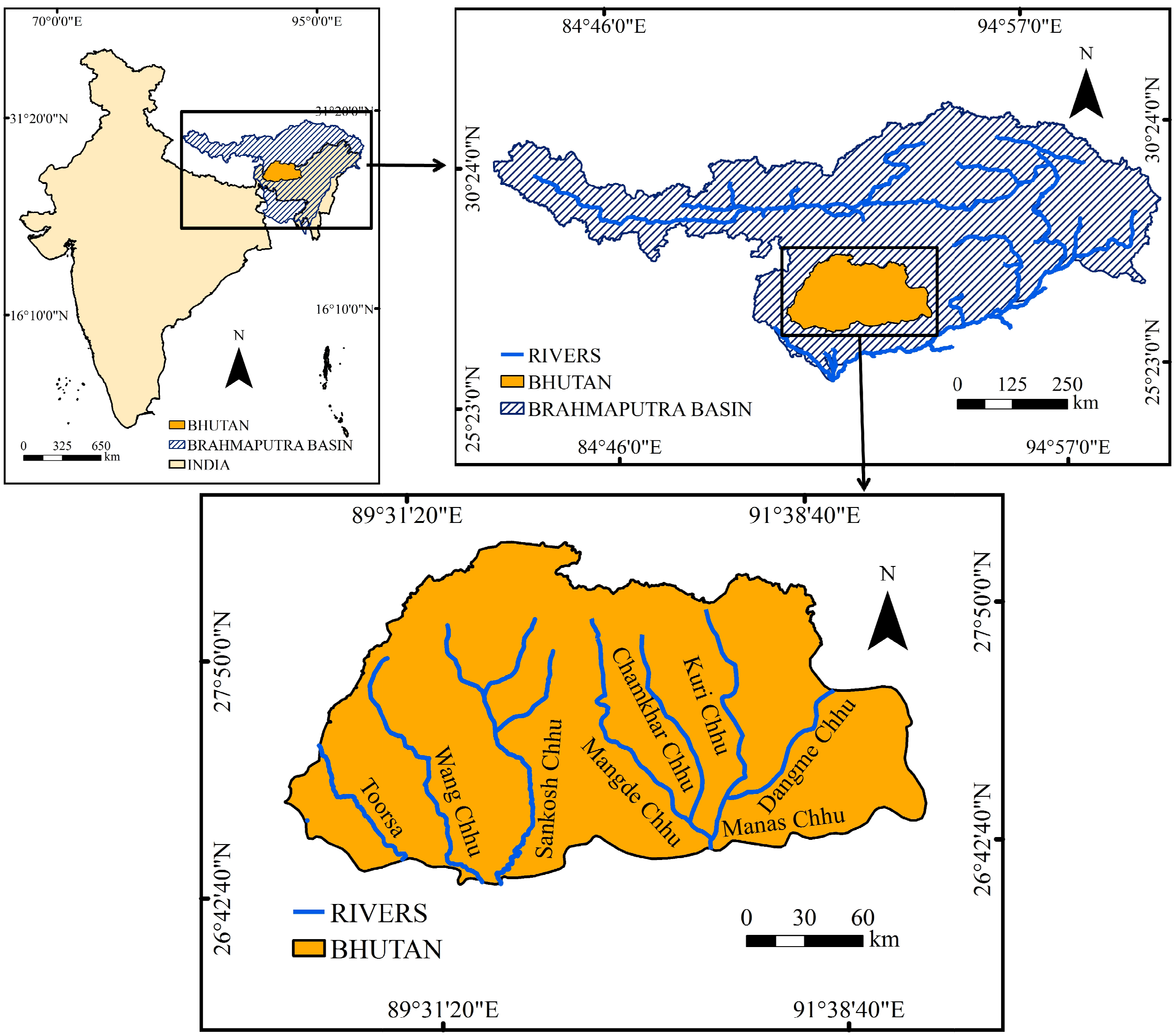
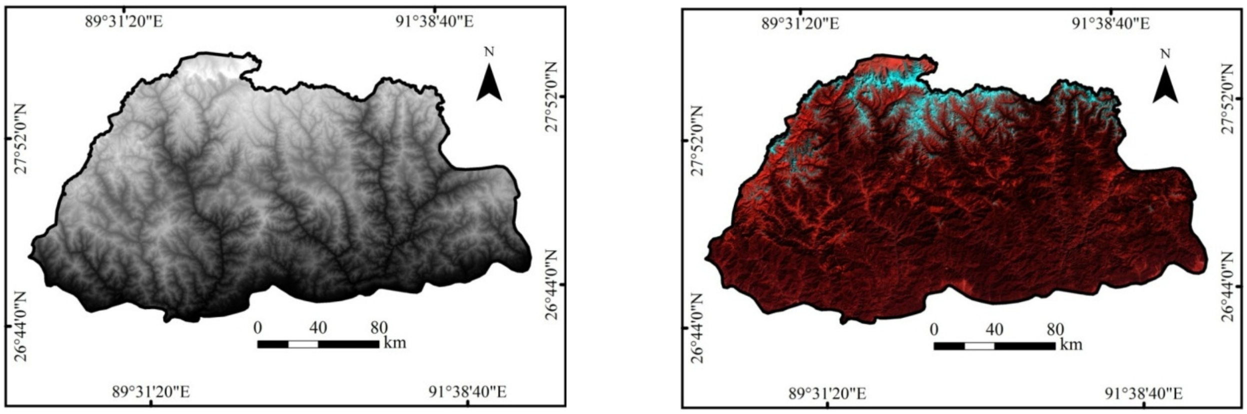


Figure-1
Study Area

Preparation and integration of these primary layers through visual interpretation was carried out in GIS and these layers were grouped into three categories: i. Base Map Information, ii. Hydrological Information, iii. Glacier and De-glaciated valley features[18].

On screen visual interpretation was carried out for mapping and delineation of the glaciers and their morphological features. The first set of satellite data was used for mapping all the glacial features. For any gap areas or in case of non-availability of cloud free data the second set of satellite data was referred. Thus, for the preparation of final datasheet in GIS environment, for each glacial feature systematic observations were made and their areas were recorded in a tabular format which was then linked via unique glacier identification number to the corresponding glacier. The approach followed in the present work was depicted in the flowchart (Figure-3).



(A) Shuttle Radar Topography Mission (SRTM) DEM (B) Advanced Wide Field Sensor (AWiFs) Image

Figure-2
Satellite data used for Glacier analysis (A & B)

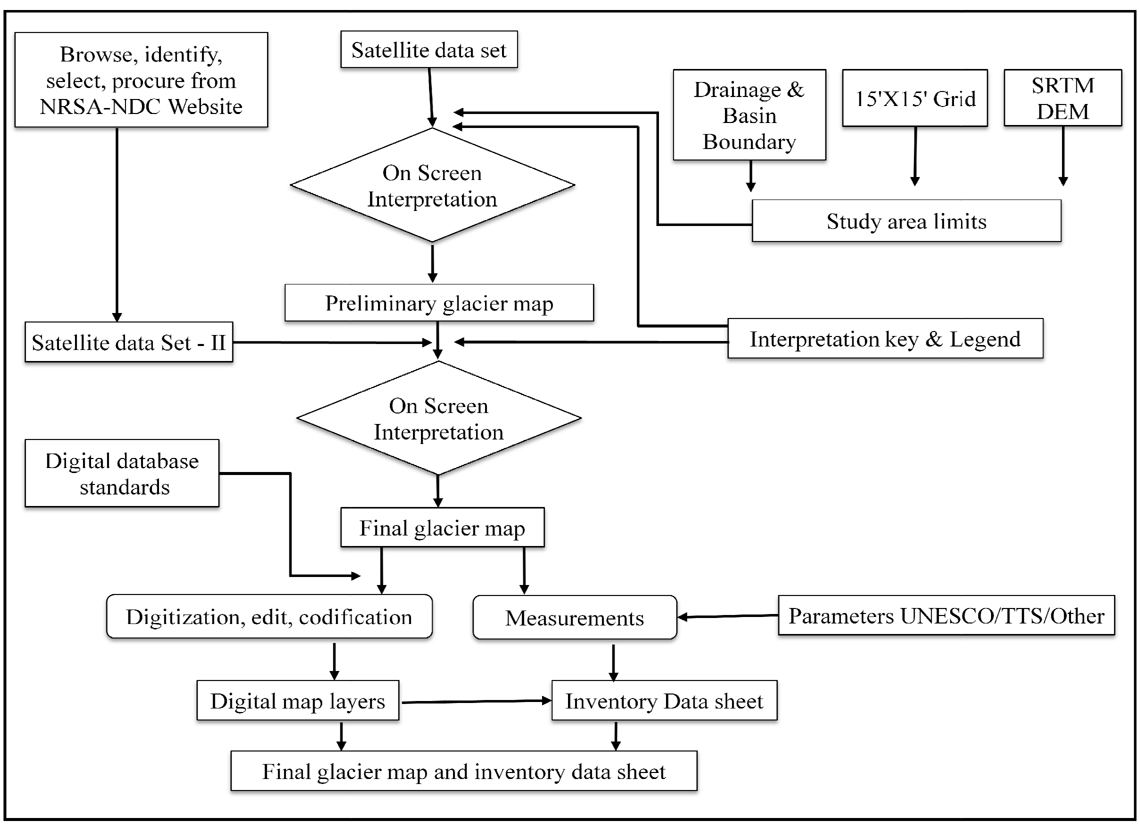


Figure-3
Workflow for glacier inventory and datasheet

Results and Discussion

Bhutan: The glaciated area of Bhutan was only 3702.33 sq. km. which is approximately 9% of the total area of the study area (Table-1); similar results were computed by GLIMS (Global Land Ice Measurements from Space) as well[19]. Inventory of 1151 glaciers was prepared where glaciers of varying sizes exist ranging from very small "Simple Basin" glaciers of 0.11 sq. km. to very large "Compound Basin" glaciers of 121 sq. km.. The total accumulation area was recorded as 60.22% of the total glaciated area which was much higher than the total ablation area of the basin i.e. 39.34% of the glaciated region. The ablation area-debris covered (79.76%) was much higher than the ablation area – ice exposed (20.25%) pointing towards the overall stability of these glaciers. 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-4.), indicative of the fact that though large in numbers but these lakes cover a very small part of the glaciated region.

The regional scenario is better understood by dividing the glaciated areas of Bhutan into three major Physiographic divisions.

Chomolhari-Kulha Gangri Region (North): As this region was located in the Greater Himalayas the number of glaciers recorded were maximum (432) with extensive glaciated area (2471.46 sq. km.). In this region the total accumulation area (62.73%) exceeded the total ablation area (36.97%) (Table-2). Supra Glacial Lakes in the Chomolhari region though huge in number (43) were not a potential danger for lake outbursts as they covered a very small area of about 0.51% only. The Rose diagram (Figure-5) which was plotted to show the direction of the glaciers, indicated that approximately 41.20% glaciers were oriented towards the north-east and east direction.

Table-1
Broad Approach for glacier inventory and Datasheet of Bhutan

No. Of Glaciers	1151
Glaciated Area (sq. km.)	3702.33
Accumulation Area (%)	60.22
Ablation Area (%)	39.34
Ablation-Debris (%)	79.76
Ablation-Ice Exposed (%)	20.25
No. of Supra Glacial Lakes	60
Supra Glacial Lakes (%)	0.42
Source: Computed	

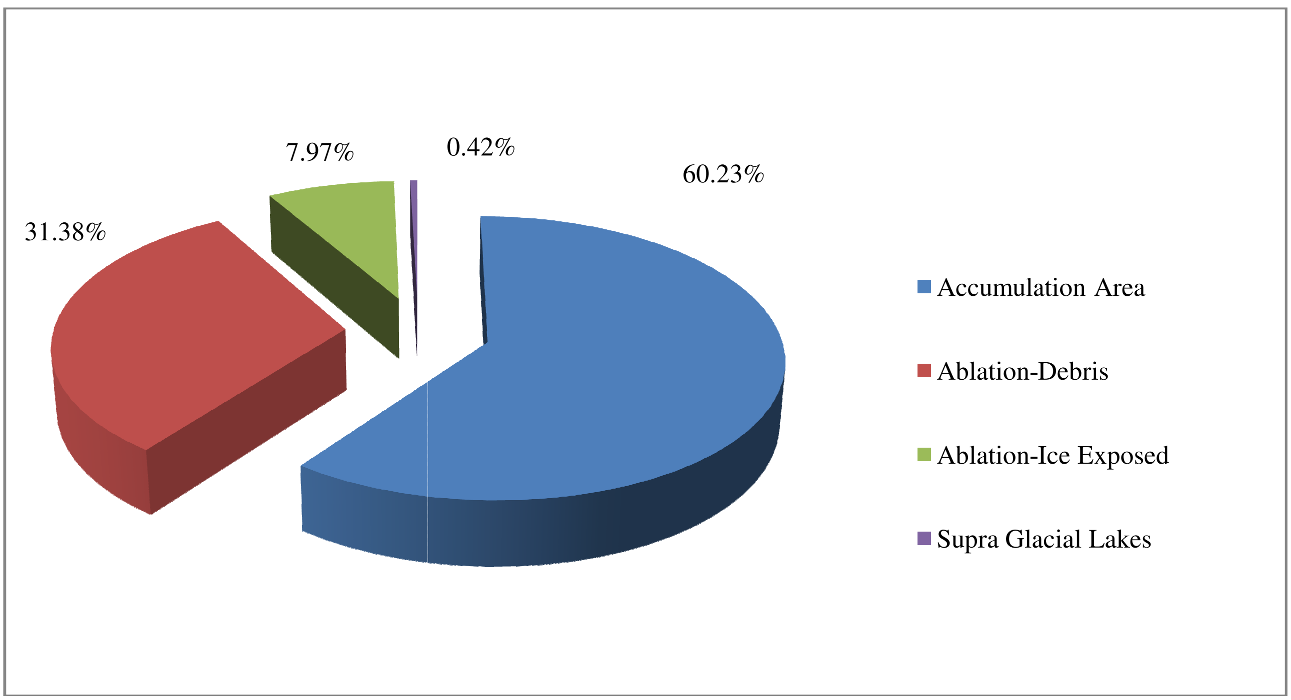


Figure-4
Sub-Basin Characteristics of Bhutan

Table-2
Glacier Statistics of Chomolhari-Kulha Gangri Region

No. 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	

Trongsa Region (West): In line with the Sikkim Himalayas this region had the second highest number of glaciers in Bhutan (378) with a glaciated area of 594.87 sq. km. The accumulation area was 55.70% whereas the ablation area was 43.76%. In comparison with the Chomolhari-Kulha Gangri region the supra glacial lakes were the second highest in number (10) but the area covered by them (0.37%) was greater (0.37%) (Table-3). Here again most of the glaciers were oriented to the north-east (approximately 37.30%) and east (approximately 34.60%) while 48 glaciers were observed to be oriented towards the north (Figure-6).

Table-3
Glacier Statistics of Trongsa Region

No. 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	

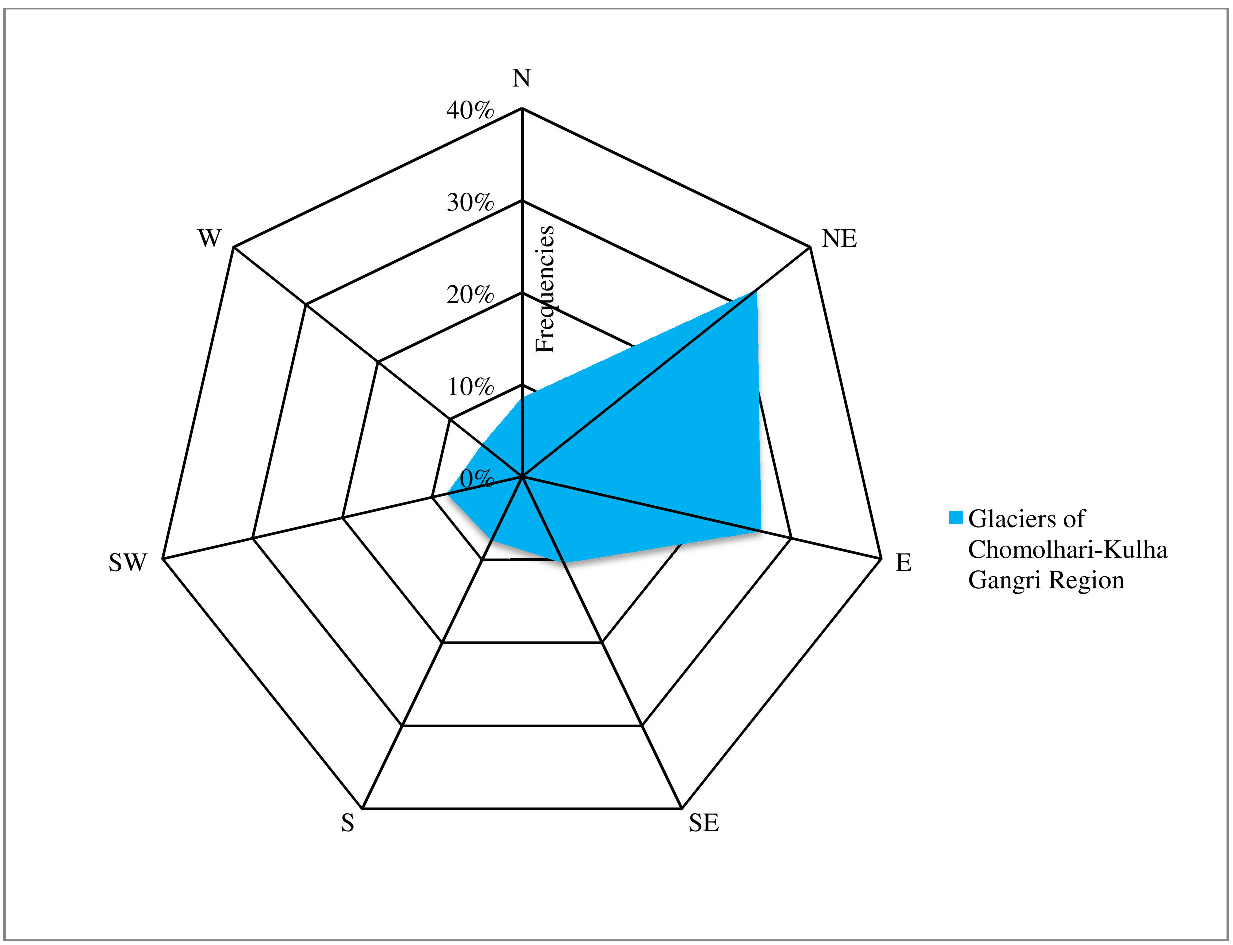


Figure-5
Rose Diagram representing Glacier Orientation of Chomolhari-Kulha Gangri Region

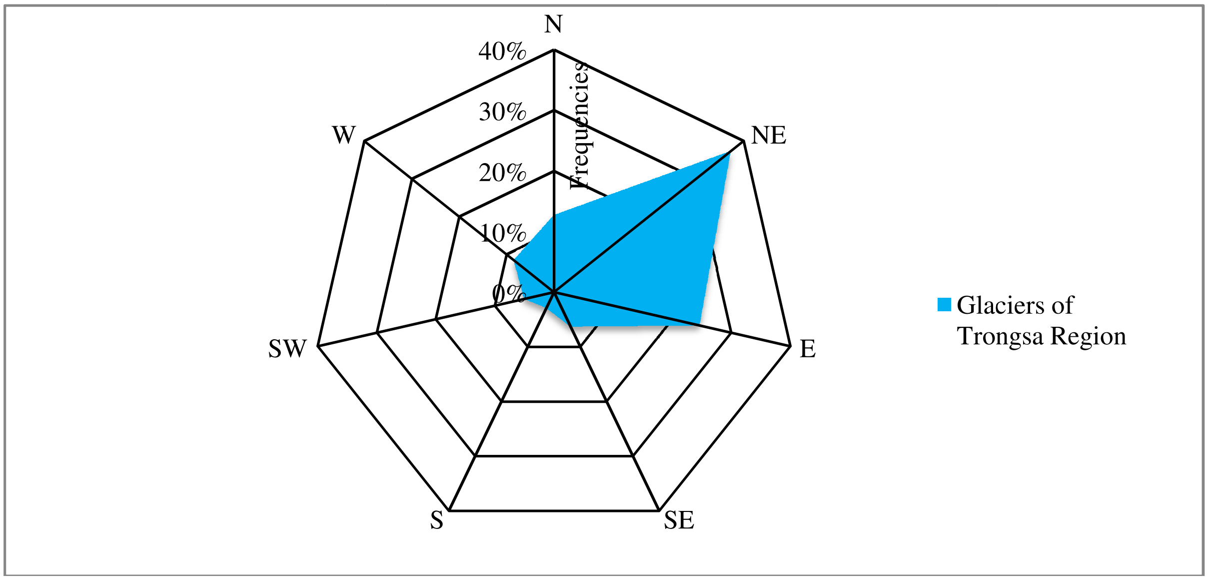


Figure-6
Rose Diagram representing Glacial Orientation of Trongsa region

Punakha-Thimphu Region (East): Located in the eastern part of the Kingdom of Bhutan this region had the least number of glaciers (341), but the total glaciated area was more (636 sq. km.) than the Trongsa region (Table-4). This is thus indicative of the fact that the average glacier size of the Punakha-Thimphu region is higher than the Trongsa region. The ablation area was recorded 44.41% and the accumulation area calculated was 55.47%. The number of Supra glacial lakes was the least in this region occupying an area about 0.12%. Maximum number of the glaciers in this region had their orientation towards the north-east (40.47%) followed by east and north oriented glaciers (Figure-7).

Table-4
Glacier Statistics of Punakha-Thimphu region

No. 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-8 symbolized the comparative analysis of the three glaciated physiographic regions of Bhutan. This statistical analysis in the form of graph made the fact apparent that positive mass balance existed in this region as the accumulation area was much higher than the ablation area[20]. The observations of the rose diagrams were therefore related with the belief that North facing glaciers increase in thickness (although some decrease, but at a slower pace) than the South facing glaciers[21].

Conclusion

Glacier Inventory of Bhutan represented 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.

The extensive glaciated area (3702.33 sq. km.) of Bhutan Himalayas was covered by 1151 glaciers giving an average glacier size of about 3 sq. km. Approximately 0.42% of the total glaciated area of Bhutan was covered with supra glacial lakes, which seems to be a small area but the danger of Glacial Lake Outburst Floods (GLOFs) still persists.

The statistics showed that the accumulation area was much greater than the ablation area (inclusive of debris covered and ice-exposed) which points towards the good health of the glaciers of this region. Maximum large glaciers were concentrated in the northern part of Bhutan where the great Himalayas exist. The general orientation of the glaciers irrespective of the regional distribution was north-east and east with some glaciers facing towards the North too.

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

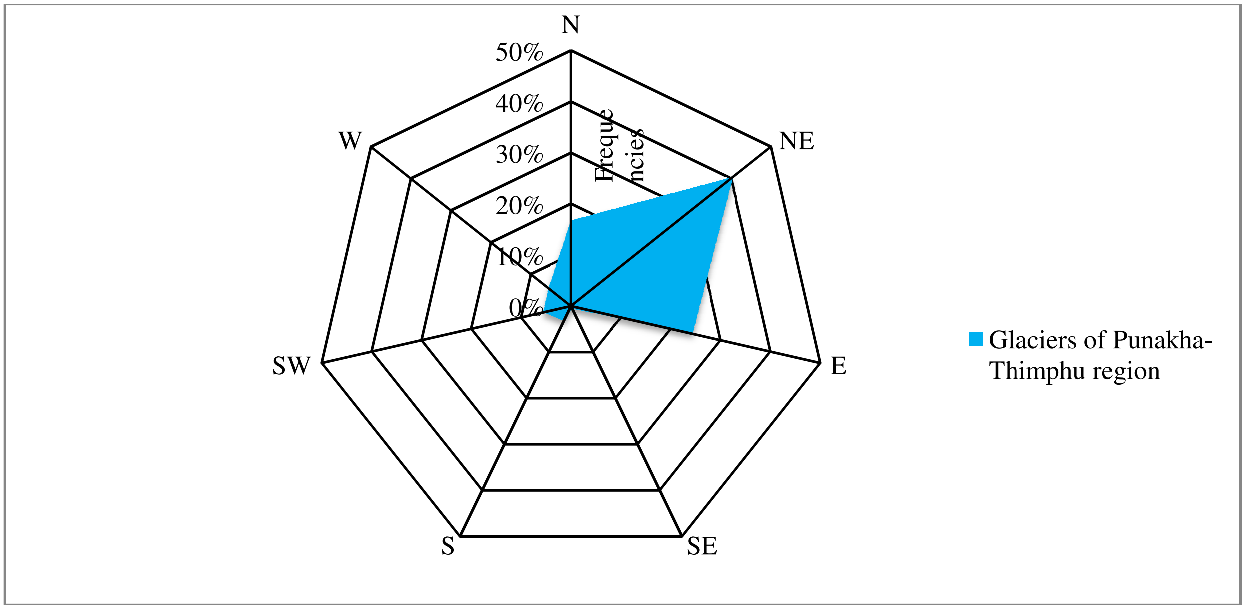


Figure-7
Rose Diagram representing Glacial Orientation of Punakha-Thimphu region

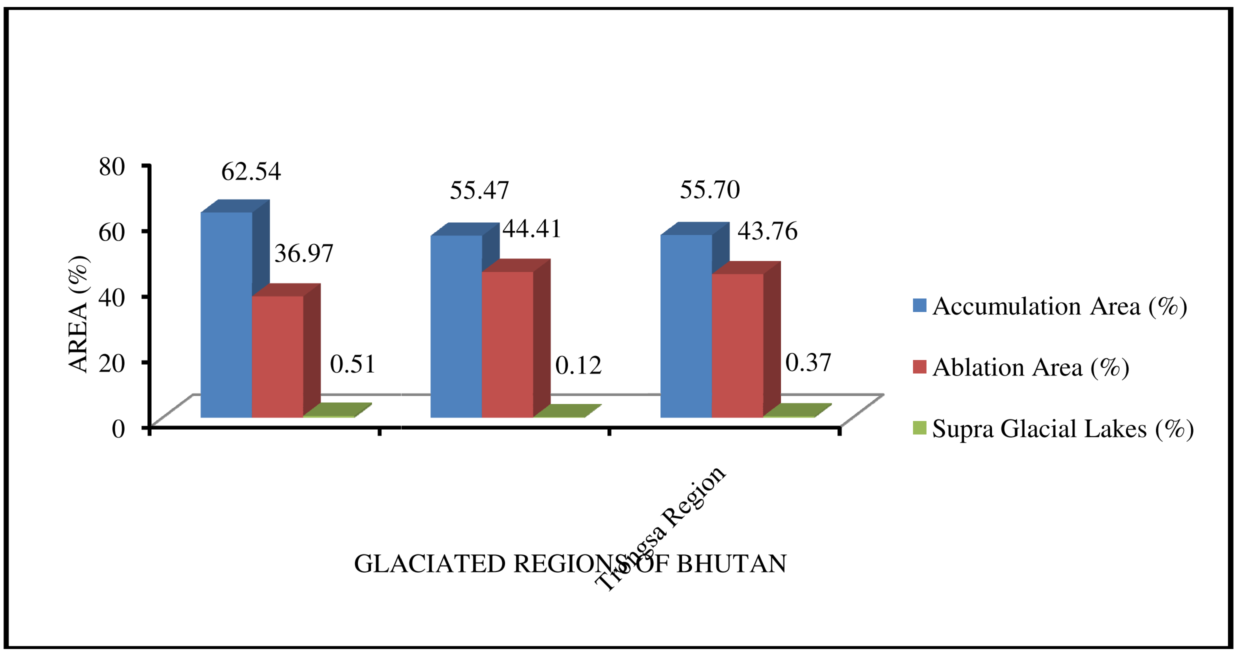


Figure-8
Comparative Analysis of Glaciated regions of Bhutan

References

1. Shrestha K.L. (2005). #Global change impact assessment for Himalayan mountain regions for environmental management and sustainable development.# Global Environmental Research-English Edition, 9(1), 69.
2. Shrestha A.B. and Aryal R. (2011). #Climate change in Nepal and its impact on Himalayan glaciers.# *Regional Environmental Change*, 11(1), 65-77.
3. Nesje A., Dahl S.O., Andersson C. and Matthews J.A. (2000). #The lacustrine sedimentary sequence in Sygneskardvatnet, western Norway: a continuous, high-resolution record of the Jostedalsbreen ice cap during the Holocene.# *Quaternary Science Reviews*, 19, 1047-1065.
4. Kaser G., Cogley J.G., Dyurgerov M.B., Meier M.F. and Ohmura A. (2006). #Mass Balance of glaciers and ice caps

Consensus estimates for 1961-2004.# *Geophysical Research Letters*, 33, 1-5.

5. Barnett T.P., Adam J.C. and Lettenmaier D.P. (2005). #Potential impacts of a warming climate on water availability in snow dominated regions.# *Nature*, 438(7066), 303-309.

6. Roy S.S. and Balling R.C. (2005). #Analysis of trends in maximum and minimum temperature, diurnal temperature range, and cloud cover over India.# *Geophysical Research Letters*, 32, L12702, doi: 10.1029/2004 GL022201.

7. Yadav R.R., Park W.K., Singh J. and Dubey B. (2004). #Do the western Himalayas defy global warming?.# *Geophysical Research Letters*, 31, 17, 10.1029/2004GL020201.

8. Dozier J. (1984). #Snow reflectance from Landsat-4 Thematic Mapper.# *IEEE Trans. Geosciences and Remote Sensing*, GE-22, (3), 323-328.

9. Hall D.K., Chang A.T.C. and Siddalingaiah H. (1988). #Reflectance of glaciers as calculated using Landsat-5 Thematic Mapper data.# *Remote Sensing of Environment*, 25, 311-321.

10. Ostream G. (1975). #ERTS data in Glaciology-An effort to monitor glacier mass balance from satellite imagery.# *Journal of Glaciology*, 15(73), 403-415.

11. Central Intelligence Agency (2015). #The World Factbook 2014-15.# Government Printing Office.

12. Singh R.L. (2008). #India: a regional geography.# National Geographical Society of India, 489-492.

13. Muller F. (1978). #Instructions for compilation and assemblage of data for a world glacier inventory Supplement identification/glacier number.# Department of Geography, Swiss Federal Institute of Technology, Zurich, 25.

14. Norbu C. (2003). #A provisional physiographic zonation of Bhutan.# University of Cambridge, http://www.dspace.cam.ac.uk/handle/1810/226999.

15. RGOB (Royal Government of Bhutan) (1991). #Land Act of Bhutan.# Thimphu, Bhutan, Department of Survey and Land Records.

16. Bahuguna I.M., Kulkarni A.V., Arrawatia M.L. and Shresta D.G. (2001). #Glacier Atlas of Tista basin (Sikkim Himalayas).# SAC/RESA/MWRGGLI/SN/16, Ahmedabad, India.

17. Kulkarni A.V., Rathore B.P., Mahajan S. and Mathur P. (2005). #Alarming retreat of Parbati Glacier, Beas basin, Himachal Pradesh.# *Current Science*, 88(11), 1844 1850.

18. Sharma A.K., Singh S. and Kulkarni A.V. (2008). #Approach for Himalayan Glacier Inventory using remote sensing and GIS techniques.# Proceedings of International Workshop on Snow, Ice, Glacier and Avalanches, IIT-B. Tata McGraw-Hill Publishing Company Ltd, New Delhi, 177-185.

19. Kargel J.S. (2014). #Global Land Ice Measurements from Space.# Springer.

20. Dixon L. and Ambinakudige S. (2015). #Remote Sensing Study of Glacial Change in the Northern Patagonian Icefield.# *Advances in Remote Sensing*, 4(4), 270.

21. Phan V.H., Lindenbergh R.C. and Menenti M. (2014). #Orientation dependent glacial changes at the Tibetan Plateau derived from 2003–2009 ICESat laser altimetry.# *The Cryosphere Discussions*, 8(3), 2425-2463.

The Deccan Geographer
Vol. 53, No. 1, June, 2015, Pp.29-37
(ISSN-0011-7269)

STUDY OF GLACIER INVENTORY FOR TISTA RIVER BASIN USING REMOTE SENSING AND GIS TECHNIQUES

Vanya Bajpai, Rolee Kanchan and A.K. Sharma

Abstract

Himalayan region is difficult to study by conventional methods due to tough terrain and extreme weather conditions. Therefore, the use of remote sensing technique is most appropriate to monitor Himalayan snow and glacier cover. Glacier inventory was carried out in the Brahmaputra river basin on 1: 50,000 scale using images of Indian Remote Sensing Satellite in a Geographic Information System (GIS) environment. As per the United Nations Temporary Technical Secretariat (UNESCO/TTS) format, the GIS database contains 37 major and 11 additional parameters. The present paper brings out the methodology adopted and salient results of the glacier inventory carried out for the Tista sub- basin located in south Brahmaputra basin in Sikkim Himalayas covering a small area of 8464 km². With almost 6.50 percent of total ice volume; Tista is the fifth largest sub-basin of Brahmaputra in terms of its solid fresh water storage. Assessment of various glacier characteristics like glacier dimension, orientation, altitude, mean slope and aspect, glacier features and de-glaciated valleys has been done with multi-date satellite data of 2006-08 in GIS environment using Indian Remote Sensing Satellite Linear Imaging Self Scanning (LISS) – III, Advanced Wide Field Sensor (AWiFS), Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM). Results showed that Tista sub-basin with 394 glaciers, range from very small glaciers of 0.1328 km² to very large glaciers of 155.7 km², have a total glaciated cover of 1321.40 km². These glaciers largely face towards the east and north-east although some facing towards the west and south-west were also observed. Glaciers in this basin start at an elevation of about 2837 meters and go up to an elevation of 7282 meters. The ablation area is lower as compared to accumulation area indicating the good health of the basin.

Introduction

Glaciers are important and direct source of information on climate change (Nesje and Dahl, 2000). The Himalayas and other mountain chains of Central Asia support large regions that are glaciated. These glaciers provide critical water supplies to arid regions of Mongolia, Western China, Pakistan, Afghanistan and India. Monitoring their evolution is a key issue as the melting of all glaciers in central Asia may significantly contribute to ongoing rise in sea level (Kaser et al., 2006). Changes in glacier length, areal extent or mass balance can also be used as climatic indicators in a region where climatic series (temperature, precipitation) are rare and the indicators are clear (Roy & Balling, 2005; Yadav et al., 2004). Measuring ongoing glacier depletion is a first step toward the prediction of future water resources in this area and has, thus, important social and economical impacts (Barnett et al. 2005). Yet, mass balance of Himalayan glaciers is very poorly sampled on the field because of the use of manual methods. Thus, satellite data based inventory of glaciers at regular intervals is an efficient way not only to map these resources but also to detect the changes in glacial dimensions because of the changing global environmental scenario. The technique of remote sensing has been efficiently used to identify and map various features of the glaciers. Application of remote sensing technique has been established in glacial studies and used extensively for glacier mapping (Ostream, 1975; Dozier, 1984; Hall et al. 1988). Multi-temporal IRS LISS III, AWiFS, SRTM DEM and ancillary data have been the main inputs for generating glacier morphological maps. Various glaciological features like accumulation area, ablation area, snout, permanent snow fields, de-glaciated valleys, various types of moraines were mapped from the false color composite of the satellite data. Inventory data of Tista sub-basin is generated for individual glaciers in a well-defined format with 37 parameters like glacier identification in terms of number and name, location of the glacier in terms of the co-ordinate details, information of the elevation above the mean sea level, dimensions like the length and width of ablation and orientation of glacier are some of the major parameters as suggested by UNESCO/TTS. Later it incorporated and modified with 11 additional parameters containing information related to de-glaciated valleys and glacier lakes. Final output in the form of Inventory map at 1:50,000 scale is created along with creation of (spatial/non-spatial) digital database in GIS.

Study region

The Brahmaputra, also called Tsangpo in Tibet/China, is a trans-national river and one of the major rivers of Asia. The present study was carried out for the glaciated regions of Tista River, a tributary of Brahmaputra originating from mount Kanchanjunga situated in Nepal. Draining an area of about 12,540 km² including the states of Sikkim and West Bengal. Tista River traverses a length of 309 km. With a basin area of about 8464 km^2, the Tista sub-basin covers 1.34 percent of the total Brahmaputra basin. It is the only glaciated sub-basin of Brahmaputra which is entirely located in India. Its glaciated area starts from an elevation of about 2837 m. Tista has plentiful fresh water storage in glacier form which can be efficiently used for hydroelectricity generation, irrigation, drinking and industrial purposes.

Objective

The objective of this present paper is to study the glacial characteristics of study region and make comparative analysis the results.

Detabase and methodology

Indian remote sensing satellite data for two consecutive years of 2006-08 period has been used to characterize and identify the glacier inventory maps. Geocoded IRS LISS III data of July to September (i.e. end of the ablation season), was used to map the glaciological features with standard band combination of Band 2 (0.52-0.59 μm), 3 (0.62-0.68 μm) and 4 (0.77-0.86 μm) and digital data with additional SWIR band (1.55-1.70 μm). Wherever cloud free images were not available, other sensor data like AWiFS were also used for selected regions over the study area. Wherever IRS Satellite data of 2006-08 July and September was not available for few map sheets, data of different time frames (January 2006-08) were also used. In addition to the satellite data, collateral data such as drainage maps from Irrigation

Table–1 : Theme Layers for Glacier Inventory Map and Datasheet Creation

Sr. No.	Theme	Remarks/Contents
(A) Base Map		
(a)	Frame work	5'×5' latitutude-longitude tic points (background for all layers)
(b)	SOI map reference	15' × 15' latitude-longitude grid and SOI reference no.
(c)	Country boundaries	Country
(d)	State boundaries	State
(e)	District boundary	District
(f)	Taluka boundary	Taluka
(g)	Roads	Metalled/unmetalled road, foot path, treks, etc.
(h)	Settlement extent	Extent of habitation
(j)	Settlement lacation	Location of habitation
(k)	Elevation DEM	Image grid
(B) Hydrology		
(a)	Drainage lines	Streams with nomenclature
(b)	Drainage poly	Water body, river boundary with nomenclature
(c)	Watershed boundary	Watershed boundary and alphanumeric codes
(C) Glacier		
(a)	Glacier boundary	Ablation, accumulation, snow cover areas, supra-glacial lake, de-glaciated valley, pro-glacial lake, etc.
(b)	Glacier lines	Ice divides, transient snow line, centre line, etc.
(c)	Glacier point	Point locations representing coordinates for glacier, glacier terminus/snout, moraine dam lake.
(d)	G lacier elevation point locations	Glacier elevation point locations, highest/lowest values for glacier, moraine dam lake, supra-glacier lakes.

Source : Authors

Atlas of India, basin boundary maps from Watershed Atlas of All India Soil and Landuse Survey (AIS & LUS), available snow and glacier maps (at 1:250,000) were used (Anon. 1990, Bahuguna et al. 2001, Kulkarni et al. 1999 and 2005, Kulkarni and Buch. 1991). Elevation information was derived from DEM, generated from the SRTM data, road maps, trekking routes, guide maps, political, physiographic maps and published literatures on Himalayan glaciers have been used. The approach followed in the study is depicted in the flowchart (Fig. 2). The glacier inventory maps basically involve preparation and integration of the primary theme layers in GIS environment at 1:50,000 scale. At this scale the Minimum Mapable Unit or minimum size of glacier feature which is mapped is 0.1 km^2. These primary theme layers are grouped into three categories, namely i) Base Map Information, ii) Hydrological Information, and iii) Glacier and De-glaciated valley features, Table–1.

The preliminary digital maps corresponding to the base map and hydrology themese were prepared using small scale ancillary data like drainage lines, watershed boundary, types of roads and settlements location. Then these preliminary theme layers were modified and finalized using multi-temporal satellite data. Systematic observations were made on each glacial features and area recorded in tabular form in the inventory data sheet in the GIS environment. The table thus generated was linked via unique glacier identification number to the corresponding glacier. Besides preparing the glacier inventory data, Accumulation Area Ratio 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).

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

Whereas: H = Volume of Ice

F = Total Glacier Area

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

Results and discussion

The glacier inventory map for the Tista sub-basin depicts the presence of glaciers and their spatial distribution. The mapped glacier features comprise of the glacier boundary giving the area of each glacier along with its morphological sub-divisions like the ablation and accumulation zones. 394 large and small glaciers in this sub-basin occupy an area of 1321.40 km^2 covering 23 Survey of India toposheets. The smallest glacier being 0.13 km^2 in area and the largest glacier occupies an area of 155.7 km^2. Majority of the glaciers in the Tista sub-basin face towards the east and north-east, though a few glaciers are also facing towards the west and south-west (Fig. 1). According to Jack D. Ives and Joe Witte glaciers

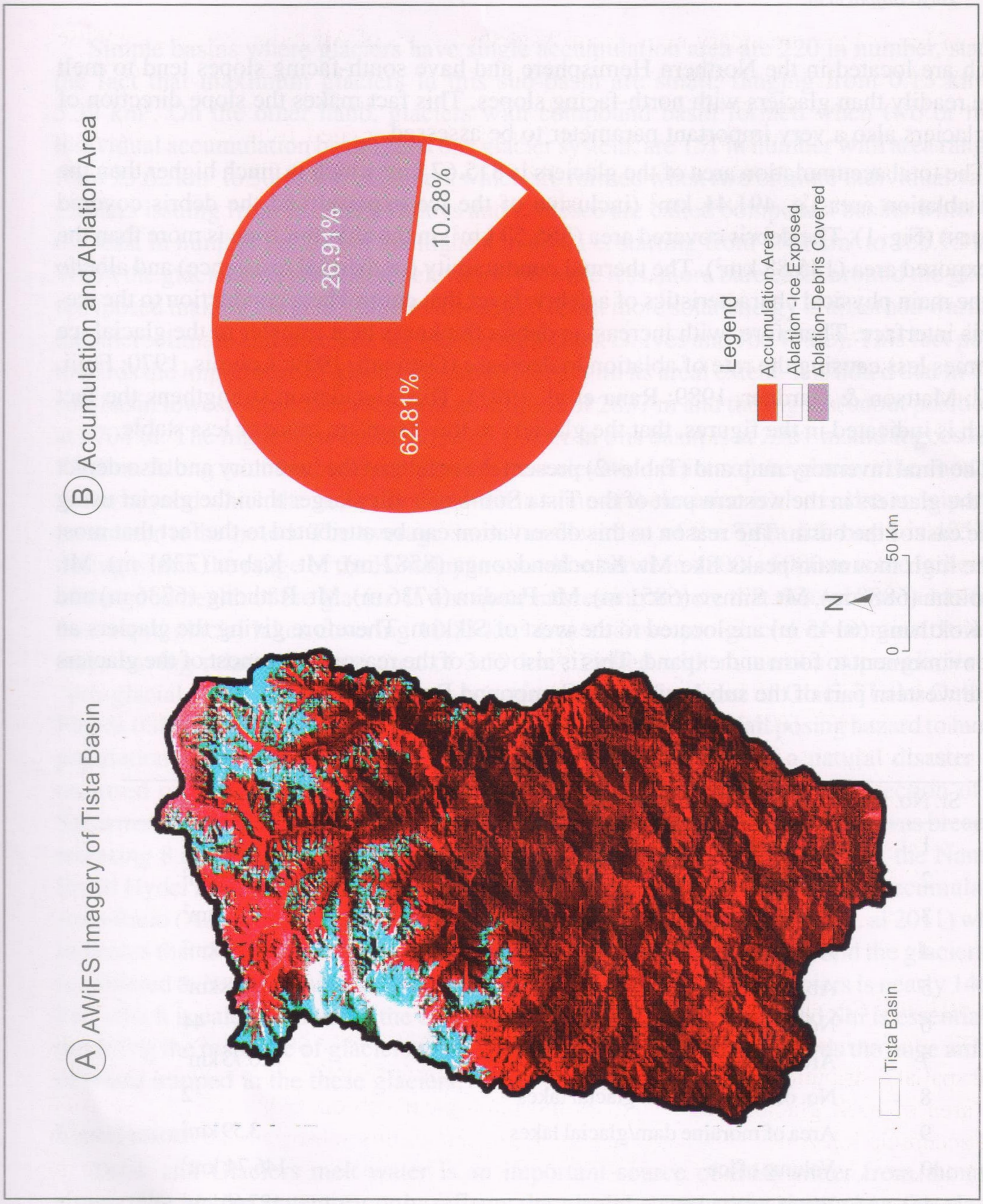

A AWiFS Imagery of Tista Basin
B Accumulation and Ablation Area
62.81%
26.91%
10.28%
Legend
Accumulation Area
Ablation-Ice Exposed
Ablation-Debris Covered
Tista Basin
0 50 km
N

Fig 1

which are located in the Northern Hemisphere and have south-facing slopes tend to melt more readily than glaciers with north-facing slopes. This fact makes the slope direction of the glaciers also a very important parameter to be assessed.

The total accumulation area of the glaciers is 815.67 km^2 which is much higher than the total ablation area i.e. 491.41 km^2 (inclusive of the ice exposed and the debris covered regions) (Fig. 1). The debris covered area (355.53 km^2) in the ablation zone is more than the ice exposed area (135.88 km^2). The thermal conductivity (or thermal resistance) and albedo are the main physical characteristics of a debris layer that control heat conduction to the ice-debris interface. Therefore, with increasing debris thickness heat transfer to the glacial ice becomes less causing the rate of ablation to decrease (Ostream, 1959; Loomis, 1970; Fujii, 1977; Mattson & Gardner, 1989; Rana et al. 1997). This elucidation strengthens the fact which is indicated in the figures, that the glaciers in this basin are more or less stable.

The final inventory map and (Table–2) present the results of the inventory and also depict that the glaciers in the western part of the Tista Sub-basin after larger than the glacier using to the east of the basin. The reason to this observation can be attributed to the fact that most of the high mountain peaks like Mt. Kanchendzonga (8582 m), Mt. Kabru (7381 m), Mt. Siniolchu (6888 m), Mt. Simvo (6851 m), Mt. Pandim (6736 m), Mt. Rathong (6736 m) and Mt. Kokthang (6145 m) are located to the west of Sikkim. Therefore giving the glaciers an apt environment to form and expand. This is also one of the reasons why most of the glaciers of the western part of the sub-basin have Compound Basins.

Table–2 : Results of Glacier Inventory

Sr. No.	Selected Characteristics	Statistics
1	Total 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
6	No. of supra - glacier lakes	44
7	Area under supra - glacier lakes	10.73 km^2
8	No. of moraine dam/ glacial lakes	2
9	Area of moraine dam/glacial lakes	3.59 km^2
10	Volume of ice	146.74 km^3
11	Water equivalent	127.66 km^3
12	Accumulation area ratio (AAR)	0.62

Source : *Computed by Authors*

Simple basins where glaciers have single accumulation area are 220 in number, stating the fact that maximum glaciers in this sub-basin are small, ranging from 0.13 km^2 to 5.39 km^2. On the other hand, glaciers with compound basin formed when two or more individual accumulation basins feed one glacier system, are 151 in number with area ranging from 23.62 km^2 to 30.18 km^2. Glaciers which are formed when two or more individual valley glaciers issuing from tributary valleys and coalesce are called compound basins which are the least in number i.e. 23 but the highest in area i.e. starting from 3.43 km^2 to 155.75 km^2. When the glacial area and glacier elevation both are less, more bare earth around the glacier is exposed making the area's albedo lower, as a result more solar energy is absorbed warming the microclimate and accelerating glacier melt (Jack D. Ives and Joe Witte). This fact points towards the importance of glacier elevation along with its areal extent. It is noted that in Tista sub-basin lowest snout elevation is at an altitude of 2837 m and the highest snout position is at 5704 m. The highest elevation point of glacier in this basin is at 2961 m and it goes up to 7282 m. Along with the highest and the lowest elevation points of the glaciers the snowline (point beyond which the snow does not melt in summers) elevation is also is also an important parameter to be noted. The average snowline elevation of the Tista sub-basin is 4853 m, falling within the range of the Himalayan snowline between 4800 – 6000 m is the indication of the good health of the glacier. It was quite interesting to note that this sub-basin has forty four supra glacial lakes covering 10.73 km^2 area and two pro-glacial or moraine dammed lakes having relatively large area of 3.59 km^2. Dotted with numerous supra-glacier and "pro-glacial lakes" Tista sub-basin is constantly under the threat of Glacial Lake Outburst Floods (GLOF). These floods occur if the terminal moraine dams fail posing hazard to human population living nearby. This fact is supported by an instance of a natural disaster that occurred on August 4, 1985 in the Dig Tsho (Tsho-lake), in the western section of the Sagarmatha (Mt. Everest) National Park, Khumbu Himal, Nepal. The moraine was breached releasing 8 million cubic meters of water that rushed downstream destroying the Namche Small Hydel Project and claiming 5 lives (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) which indicates that the glaciers in this basin experience relatively less melting and the glaciers are considered to be "in balance". The total volume of ice tied up in the glaciers is nearly 146.14 km^3 which is calculated using the equation devised by Liu and Ding and Shi is essential for modeling the response of glaciers to climate change and also hints towards the huge amount of water trapped in the these glaciers.

Conclusion

Snow and Glaciers melt water is an important source of fresh water from mountain rivers. The glacier inventory only reflects the glacial status at the time when the glaciers were mapped. For any application of such data we need to take into account of the changing status of the glaciers.The inventory of the Tista sub-basin in the Brahmaputra basin gives an information about the different features contained within the glaciers. All the glacier parameters in detail are calculated. Most time-consuming job is the manual digitizing of glacier length. Parameters like the orientation of the glaciers, elevation both maximum and minimum, the maximum and minimum width of the glaciers etc. provide additional information and are very useful for practical purposes. Thus, inventory providing such huge database is a very important asset in the world of glaciers. Whereas, there is always a scope to add more information which can be about the mean depth and volume, which can answer a number of critical questions (e.g. sea-level change etc.). In view of the rapid changes taking place in the cryosphere, the 50 years originally conceived as an appropriate re-inventory interval needs to be reconsidered. The rapid adoption of satellite-based techniques should allow for the much more frequent inventories that are now desired. Thus, Glacier Inventory of this level should be done at least on decadal basis with high-resolution optical as well as Synthetic Aperture Radar (SAR) imagery. The results of this database can be used to update the Himalayan glacier database, providing more information to researchers working for glacial dynamics and climate change. The data can also be used in models for identifying potential sites for hydroelectricity generation, irrigation water needs and other uses like industrial and domestic uses.

References

Anon, (1990) : "Watershed Atlas of India, All India Soils and Landuse Survey" Ministry of Agriculture and Cooperation, Govt. of India.

Bahuguna, I.M., Kulkarni, A.V., Arrawatia, M.L. and Shresta, D.G., (2001) : "Glacier Atlas of Tista basin (Sikkim Himalayas)" SAC/RESA/MWRG-GLI/SN/16/2001.

Himalayan Glaciers and Glacial Lakes: Case Studies on GLOF and Associated Hazards in Nepal and Bhutan. Kathmandu" International Centre for Integrated Mountain Development and United Nations Environmental Programme Regional Office Asia and the Pacific (ICIMOD Publication 169).

Barnett, T., J. Adam, and D. Lettenmaier. (2005) : "Potential Impacts of a Warming Climate on Water Availability in Snow Dominated Regions" Nature, 438(7066), Pp. 303-309

Hall, D. K., Chang, A.T.C., Siddalingaiah, H. (1988) : "Reflectance of Glaciers as Calculated Using Landsat -5 Thematic Mapper Data" Remote Sensing of Environment, 25, 311321.

Kang E., Lui C., Xie Z., Li X., Shen Y. (2009) : "Assessment of Glacier Water Resources Based on the Glacier Inventory of China" Annals of Glaciology 50(53), Pp. 108-'109.

Kaser, G., Cogley J. G., Dyurgerov M. B., Meier M. F. and Ohmura A. (2006) : "Mass Balance of Glaciers and Ice Caps Consensus Estimates for 1961-2004" Geophysical Research Letters 33: 1-5.

Kulkarni, A.V., Rathore, B. P., Mahajan, S. and Mathur, P. (2005) : "Alarming Retreat of Parbati Glacier, Beas basin, Himachal Pradesh" Current Science 88(11), Pp. 1844 1850.

Kulkarni, A.V. and Buch, A.M. (1991) : "Glacier Atlas of Indian Himalaya" SAC/RSA/RSAGMWRD/SN/05/91, P. 62.

Nesje, A., Dahl, S.O., Andersson, C., Matthews, J.A. (2000) : "The Lacustrine Sedimentary Sequence in Sygneskardvatnet, Western Norway: A Continuous, High-resolution Record of the Jostedalsbreen Ice - cap during the Holocene" Quaternary Science Reviews 19, Pp. 1047-1065.

Ohmura, A. (2009) : "Completing the World Glacier Inventory" Annals of Glaciology 50(53). P. 144.

Ostream, G. (1959) : "Ice Melting Under a Thin Layer of Moraine, and the Existence of Ice Cores In Moraine Ridges" Geogr. Ann.41(4), Pp.228-230.

Racoviteanu, E.A., Paul F., Raup B., Khalsa S. J. S., Armstrong R.(2009) : "Challenges and Recommendations in Mapping of Glacier Parameters from Space: Results of the 2008" Global Land Ice Measurements from Space (GLIMS) Workshop, Boulder, Colorado,USA. Annals of Glaciology 50(53), P. 66.

Rana, B., Nakawo, M., Fukushima, Y. & Ageta, Y. (1997) : "Application of a Conceptual Precipitation - Runoff Model (HYCYMODEL) in a Debris-covered Glacierized Basin in the Langtang Valley, Nepal Himalaya" Ann. Glaciol. 25, Pp. 266-231.

Roy, S. S. and R. C. Balling Jr. (2005) : "Analysis of Trends in Maximum and Minimum Temperature, Diurnal Temperature Range, and Cloud Cover Over India" Geophysical Research Letters, 32, L12702, doi: 10.1029/2004 GL022201.

Scherler, D., Bookhagan, B. and Strecker, M. R. (2011) : "Spatially Variable Response of Himalayan Glaciers to Climate Change Affected by Debris Cover" Nature Geoscience Letters (Published online 23 January 2011).

Sharma, A.K., Singh, S. K. and Kulkarni, A.V. (2006) : "Technical Guidelines for Himalayan Glacier Inventory (Indus, Ganga and Brahmaputra Basins)" SAC/RESIPA/MESG SGP/TN 27/2006.

Sharma, A.K., Singh, S. and Kulkarni, A.V. (2008) : "Approach for Himalayan Glacier Inventory Using Remote Sensing and GIS Techniques" Procd. International Workshop on Snow, Ice, Glacier and Avalanches. Edited by Venkataraman G. and Nagarajan R., IIT-B, Tata Mc Graw-Hill Publishing Company Ltd., New Delhi, Pp.177-185.

Yadav, R.R., Park, W.K., Singh, J. and Dubey, B. (2004) : "Do the Western Himalayas defy Global Warming" Geophysical Research Letters 31: 10.1029/2004GL020201.

— Vanya Bajpai
Research Student,
Department of Geography,
M. S. University of Baroda, Baroda
(Gujrat)

— Rolee Kanchan
Professor, Department of Geography
M. S. University of Baroda, Baroda
(Gujrat)

— A. K. Sharma
Space Applications Centre (ISRO)
Ahmedabad
(Gujrat)