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Expansion of Glacial Lakes in Bhutan during 1990-2009

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Abstract

In recent decades, there are notable impacts of climate change on the glacial lakes in the Himalayan region. Therefore, the glacial lakes are expanding due to melting of the glaciers. The current study has been adapted to observe the changing pattern of glacial lakes during 1990 to 2009, which are located in the glacier mountain in Bhutan. The identification of the actual area of the lakes has been done using satellite imagery (Landsat TM and Landsat ETM+) by digitization after application of the correction methods (geometrical and radiometrical) on raw satellite images. The satellite images are utilized for the time periods of 1990, 2001, 2007 and 2009 for this study. The lake volume has been calculated using a glacial lake area and Digital Elevation Model (DEM). Finally, changes in the volume of lakes have been observed from 1990 to 2009. The highest increment of lake volume is found in the Luggye (45%) and Thorthormi (27%), while the lowest is observed in the Thorthormi-4 (1%). Overall, the highest expansion rate of glacial lakes is found in the Thorthormi-1 and Luggye around 0.036 km^2/year and the smallest were Thorthormi-2 and Thorthormi-3 around 0.005 km^2/year respectively. Higher extent (area and volume) of glacial lakes should be taken care to avoid the damage due to potential bursting.

Keywords:

1. Introduction

Himalayan glaciers are observed to be shrinking more rapidly than in other parts of the world[1]. Glacier lakes are the most noticeable and might have been the most significant consequence of climate change in the mountains. The possible outburst of such lakes is a direct threat to populations and infrastructure lying at the down streams. This paper gives an overview of the present situation and the potential danger in near future too. The development of glacial lakes and the significant consequences in case of outburst has caused widespread concern. Glacial lakes are the tip of the iceberg and it is very sensitive to climate change. It may cause gradual retreating of the storage capacity of water in glaciers during the dry season, a faster water runoff during monsoon season, and extended days with little water. The long term outcomes may affect the downstream water availability for food production and therefore, have influence on food security.

Warming of climate has caused change in the environment of this region such as lowering of glacier surfaces, glacier front retreat, changes in sea ice patterns, collapse of ice shelves[2–5]. In spite of such changes, Glacial Lake Outburst Floods (GLOFs) that are usually considered as a signal of warming of climate in Himalayas, is not yet described in the mountain regions[6–9]. Recent events of GLOFs are observed in different parts of the Himalayas, European Alps, Andes, Iceland, in the North American mountains and in central part of Asia[6,7,10–13].

In the 1970s, Augusto Gansser developed first modern descriptions of Bhutan glaciers, who carried out various geological surveys and generated a chronology of past glaciations in north of Bhutan[14,15]. The authors' in[14] also reported about the potency of glacier-lake outburst resulting in flood in the Lunana area.

In[14] the study roused an interest in the glacier study of Bhutan particularly in the north. The Geological Surveys

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of Bhutan and India conducted joint surveys of different glaciers and glacial lakes in 1984 and 1986, to assess the potential hazard from *Raphsthreng Tsho* in the Lunana area[16]. However, the report concluded no danger of flood outburst. But on 7 October of 1994, a GLOF from *Lugge Tsho* glacial lake results in demise of more than 22 people in the Punākhatown of Bhutan[17,18].

In recent decades, there was an alarming rate of retreating on glaciers of the Tibetan Plateau due to warming of climate, which not only affected water resources and hydrological processes of the region[19,20], but also results in the expansion of glacial lakes[21] and the possibility of Glacial Lake Outburst Floods (GLOFs)[22,23]. The GLOFs emerge to be significant to the people living downstream because of their hazardous effects on infrastructure and resources of society. The local climate of the south-eastern Tibetan Plateau is influenced significantly by the warm and humid moisture from the Indian Ocean, and there are retreat of many marine-type glaciers that has resulted in glacial lakes in front of glacier termini[21,24]. Recent studies in[25–28] has concluded is a rapid retreat in the Tien Shan mountains and Kush–Karakorum–Himalayan (HKH region). Some researchers have described automated or semi-automated methods to digitize glacial lakes[29,30] and glaciers[31]; however, these methods are more appropriate for larger areas while still needing manual correction.

It is expected that glaciers and ice caps are going to retreat continuously during the 21st century[32]. The retreat of the Himalayan glaciers is very rapid and they are forming many glacial lakes on the glacier toes. IPCC (1996) predicted disappearance of up to a quarter of the current mountain glacier mass by 2050 because of global warming. The authors[33] reported similar disappearance of the Himalayan glaciers by 2035 and possibly sooner, and if the warming rate of earth continues at the current rate then it will reduce from 193051 sq. miles to 38600 sq. miles by that year.

It has been observed that number of small glacier lakes is appearing and existing lakes are changing their size due to climate change. Continuation of this process will lead to merging of new lakes and formation of large lakes, aggravating the threat. About 20 glacial lakes are reported to be potentially dangerous, together with 17 lakes that found to have not experienced a prior GLOF[34]. However, spreading of these lakes might have a chance to burst in future. Rising melting rate and decreasing ice formation rate will results in drastic diminish of the amount of snow, affecting the global warming. The warnings throughout the area of TshoRolpa watershed are causing fear and uncertainty among people living in this area. The main objective of the paper is to calculate the area and volume of glacier lakes using past remote sensing data in different time periods. Identify the vulnerable lakes after analyzing the change scenario of the area and volume of lakes during 1990 to 2009.

2. Study Area

Bhutan is a princely state and is surrounded by lands in all sides. The country covers an area of 46500 km^2 and the extent is from 26°15' and 28°40' North latitudes and 88°45' and 92°10' East longitude in the Eastern Himalayas. The country is surrounded by India in south and south-west and by the Tibetan autonomous region of China in the north and north-west (Figure 1).

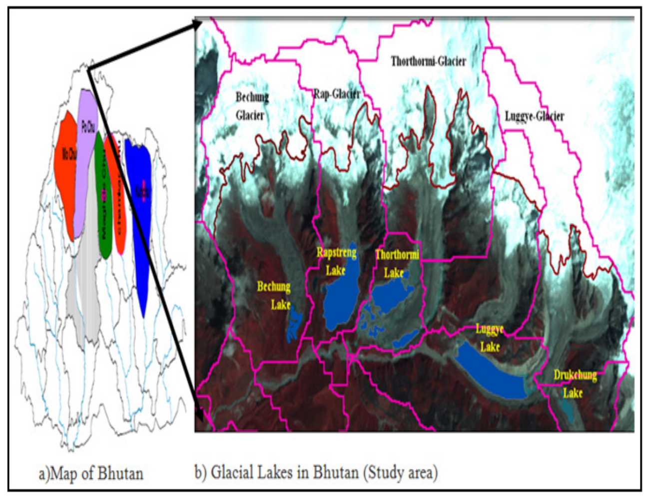

Figure 1. Study area.

Almost the whole country is mountainous, and the elevation ranging from 100 m along the Indian border to the 7554 m Kulha Gangri peak on the Tibetan border. The two extreme elevation ranges gives the landscape a condition from sub-tropical to arctic. The stretch of the country from east to west is about 300 km and is about 150 km from the north to south.

Lunana region is situated at the latitude of 28°05'30.2" and longitude of 90°11'33.56" in the northern part of country at the 4352 m Above Mean Sea Level (AMSL). Mostly the northern part of Bhutan is covered with snow throughout the year and also has glacier coverage. And there are few glaciers in which it has been noticed that rate of retreating is faster forming the potentially dangerous glacial moraine-dammed lakes at the toes of the glaciers.

3. Data and Methodology

3.1 Processing of Satellite Data

To pre-process the satellite imageries, geometric correction and radiometric rectification processes are important to facilitate comparability among dates[35]. All satellite images were geometrically registered to 1:50,000 scale topographic maps. Root mean square errors of registration were observed at 1 pixel (<30m).

The radiometric calibration and rectification processes were carried out after the geometric correction until the corrected images were found.

At the beginning, DN value is changed to spectral radiance (L_λ) after checking of the gain value using the official NASA approved ranges of $L\max_\lambda$ and $L\min_\lambda$ by the following formula[36]:

$$L_{TOA} = \left(\frac{L\max_\lambda - L\min_\lambda}{QCAL\max - QCAL\min}\right) * (DN - QCAL\min) + L\min_\lambda \quad (1)$$

Where, $L\max_\lambda$ = maximum radiance (in $Wm^{-2}sr^{-1}\mu m^{-1}$); $L\min_\lambda$ = minimum radiance (in $Wm^{-2}sr^{-1}\mu m^{-1}$); $QCAL\max$ = maximum DN value possible (255); $QCAL\min$ = minimum DN value possible (0 or 1).

Radiance value is then changed to reflectance using the following equation[37]:

$$\rho = \frac{L_{TOA}\pi d^2}{ESUN_\lambda \cos\theta_z} \quad (2)$$

Where, ρ = Reflectance; d^2 = Earth sun distance (AU); $ESUN_\lambda$ = Band dependent exoatmospheric irradiance $(Wm^{-2}\mu m^{-1})$; θ_z = Solar zenith angle (degree).

$$d = 1.001672 * \sin\left(\frac{2\pi(J - 93.5)}{356}\right) \quad (3)$$

Where, J = Julian day.

3.2 Extraction of Area and Volume of Lakes

In this study, simply using of ArcGIS 9.3, the expansion of glacial lakes was found out for different years. The Landsat TM and Landsat ETM + images of 1990, 2001, 2007 and 2009 were used for the digitization of the glacial lakes in order to see the differences (Table 1). For the watershed delineation of the study area, ASTER DEM was used in the Arc Hydro tool 9.3 as it gives more clarity of the boundary. From the digitization of glacial lakes from the landsat maps of different years, the volume calculation of each lake was done by the following method (Figure 2).

Table 1. Details of satellite imagery

Sl. No.	Sensor type	Acquired Date	Resolution
1	Landsat TM	14.11.1990	30m
2	Landsat ETM+	20.11.2001	30m
3	Landsat TM	23.12.2007	30m
4	Landsat TM	20.10.2009	30m
5	Landsat TM	25.11.2009	10m

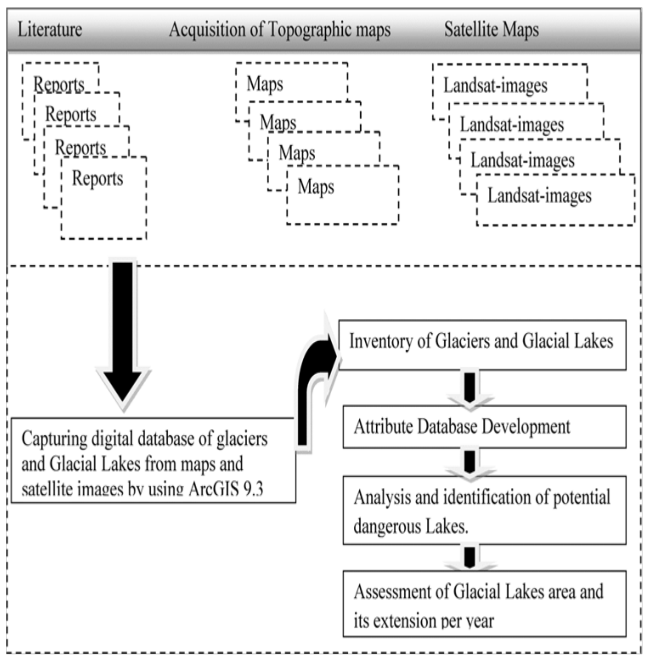

Figure 2. The flow diagram of methodology used for inventory.

No estimates are available regarding the volume of glacial lakes in Bhutan from their water spread areas. Nevertheless, some estimates for glacial lakes in Swiss Alps are available, as reported by researchers in[28]. Due to the lack of information on the volume of potentially dangerous glacial lakes in Bhutan, use of the same relationships generated for the lakes in Swiss Alps have been considered to estimate the water volume for the lakes on Pho Chu and Mo Chu sub-basins in Bhutan. The empirical relations are obtained in the study by the researcher[38].

The lake volume $V = 0.104\ A^{1.42}$ (4)

Where, V is the lake volume in m^3, A is the lake area in m^2.

The volume of potentially dangerous lakes on Pho Chu sub basin were accordingly estimated and given in Table and its rate of growing per year.

3.3 Expansion of Glacial Lakes in Lunana Region

In Lunana region, it has been observed that many debris-covered glaciers (D-types) stretch their tongues in the eastern headwaters of Pho Chuinto the flat valley floor. A contiguous chain of termini is formed by three glaciers where large glacier lakes called LuggeTsho, ThorthomiTsho, RaphsthrengTsho and BechungTsho that appeared in the late 1990s. This area is considered to be most vulnerable for GLOF as the lakes can interact with each other.

3.4 Lugge Lake and DrukchungTsho Lake

LuggeTsho, located at 28°06'N and 90°18'E, is 4520 m above the mean sea level (AMSL) and situated in the east of the Lunana valley at the head of Pochu. The following figures show the glacial lake from 1990 to 2009 for almost 21 years.

It has been observed that in the 1950s, no considerable lakes on Lugge Glacier or Drukchung Glacier that connects Lugge Glacier from the southeast were found. As reported by researchers[14], many supraglacial ponds are observed on both glaciers in the 1967. It has also given indications of recent drainage of ponds on the Drukchung Glacier. One strange thing was that the size of Drukchunglake is found to be reducing at rapid rate. LuggeTsho occupied highest area in 1993. It then shrank after the outburst in 1994, when there is a recession of nearly 500 m in the western end of the lake and from 1994 onwards it starts growing in sizes.

3.5 ThorthomiTsho Lake

Extent of the supraglacial ice-melt lakes, situated at 28°06' N and 90°17'E and 4440 m AMSL, on Thorthomi Glacier has been found to have accelerated in the 1990s. In the 2000s, acceleration is more although there was a shorter duration while in 1990, there were only four supra-glacial lakes. Again in 2001, one more glacial lake was observed. A continuous increase of the lakes was recognized by 1998 observations. Cover of thin debris over the glacier surface that accelerates ice melting, along with a very gentle gradient of the snout might cause the development of a large lake in the near future. Since in early 2009, Royal government of Bhutan has started the process of mitigation measures because of its quick acceleration in size, which resulted in its size reduction in late 2009 (Figure 3).

Figure 3. Mitigation measures of Thorthormi (source: Thorthormi mitigation project).

3.6 RapstrengTsho Lake

RapstrengTsho located at 28°0' N, 90°15'E, and 4400 m AMSL, was found to be extending rapidly. However, the lake maintained almost the same condition in the 1990s (Figure 4). Expansion of the lake was stopped, might be due to the fact that glacial bed rises steeply upstream from the current terminus position. The RaphsthrengTsho level is found to be about 50 m lower than the supraglacial lakes on the Thorthomi Glacier in the east. The moraine between them is observed to be damming water flow from Thorthomi lakes to RapstrengTsho. However, it is quite thin and there is a chance of unification of two glacial lakes. Also, break of this moraine dam will lead to the Thorthomi lake outburst that might instigate a catastrophic outburst of RapstrengTsho. Vulnerability of failure of the moraine will accelerate in case seepage from Thorthomi Glacier to RapstrengTsho weakens due to any physical factor. Although mitigation process has been carried out in 1996-1998 by artificial excavation, the risk is quite high since the lake holds a great volume of water (maximum depth is about 100 m). Addition of some volume of water at any time from the Thorthormi makes it potentially dangerous in near future.

3.7 BechungTsho Lake

BechungTsho (28°06'07.08" N, 90°13'50.52" E) at an elevation of 4335 m AMSL is situated just beside the Rapstreng Lake. It had no significance in the map of 1990s and in 2001; it appeared in very small size which was assumed to be appeared in late 1990s. Initially it was only one in 2001 and became two in 2007 and again merged into one in 2009 as in Figure 4.

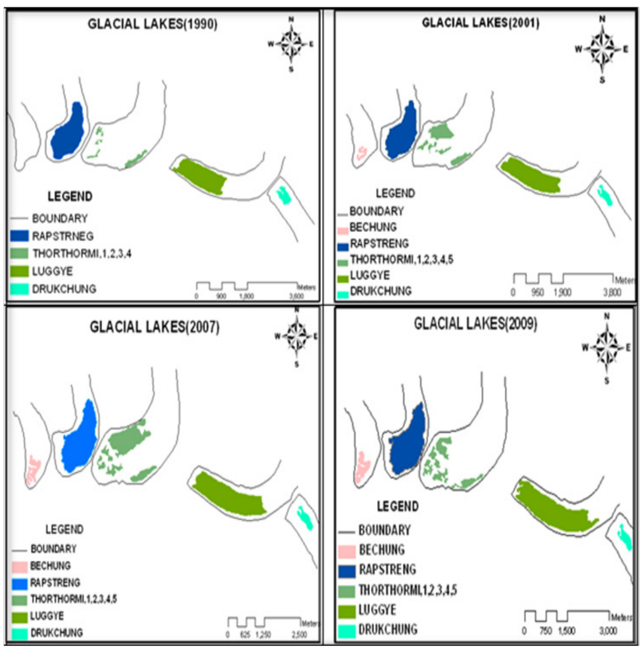

Figure 4. Glacial lakes for different years.

4. Results and discussions

4.1 Variation of Glacial Lakes

Glacial lakes can be classified according to causes of origin into three types such as, moraine-dammed, trough-valley and landslide dammed lakes. But in this study only the moraine-dammed is considered as it is mostly being blocked by debris of the glacier itself. The Table shows the variation of Glacial Lake in terms of areas, perimeter and volume for different years (Figure 5 and 6). From the year 1990 to 2009, the growth of volume in terms of percentage/year was 45% for Luggye, 27% for Thorthormi, 14% for Rapstreng, 2% for Thothormi-2, Thorthormi-3 and Thorthormi-5, 7% for Bechung, 1% for the Thorthormi-4 and decreasing rate for the Drukchung (Table 2, 3 and 4). Selected glacial lakes are increasing the perimeter, area and volume during 1990 to 2009. It can create a possibility to break the lakes and wash out the downstream area. The government authority should be taken as a serious step to protect a serious damage and they can further detail study of this area.

The following figure indicates the area of each glacial lake in particular year in the form of percentage wise. As it is shown that the highest ones are Rapstreng and luggye lakes and Thorthormi_1 kept on increasing its value till 2007 and in 2009, it dropped to 5% from 17% in Figure 7. This was because in early 2009, the Royal government of Bhutan took the mitigation measures on it as in Figure number 3 as it gives an alarming rate of increment in volume. The department of geology and mining of Bhutan

Table 2. Growth of volume of glacial Lake per year

		Location		Volume of Lakes	
Year	Names of Lakes	Latitude	Longitude	m^3/year	km^3/year
1990 to 2009	Rapstreng	28'06'24.01»N	90'14'51.76»E	450923.67	0.0006
	Thorthormi_1	28'06'21.78»N	90'15'48.95»E	1133792.23	0.0011
	Thorthormi_2	28'06'15.23N	90'15'21.95»E	83594.40	0.0001
	Thorthormi_3	28'06'06.66»N	90'15'25.61»E	83217.82	0.0001
	Thorthormi_4	28'05'52.78»N	90'16'05.16»E	34455.98	0.00003
	Luggye	28'06'02.13»N	90'15'18.08»E	1927260.32	0.0019
	Luggye_1	28'05'12.34»N	90'19'34.14»E	**-7217.10**	**-0.00001**
2001 To 2009	Thorthormi_5	28'0602.13»N	90'15'18.08»E	89547.18	0.0001
	Bechung	28'06'07.64»N	90'13'49..51»E	298432.54	0.0003

Table 3. Variation of area of different glacial lakes

Year	Names of Lakes	Elevation(m)	Area (km^2)	Difference of Area	%increment of Area
1990	Rapstreng	4368	1.14		
2001	Rapstreng	4368	1.17	0.04	3.41
2007	Rapstreng	4368	1.23	0.05	4.39
2009	Rapstreng	4368	1.25	0.03	2.38
1990	Thorthormi_1	4454	0.04		
2001	Thorthormi_1	4454	0.34	0.30	805.03
2007	Thorthormi_1	4454	0.65	0.32	94.01
2009	Thorthormi_1	4454	0.16	-0.49	-74.67
1990	Thorthormi_2	4459	0.02		
2001	Thorthormi_2	4459	0.05	0.03	165.81
2007	Thorthormi_2	4459	0.06	0.01	16.28
2009	Thorthormi_2	4459	0.08	0.02	34.44
1990	Thorthormi_3	4462	0.03		
2001	Thorthormi_3	4462	0.04	0.01	21.62
2007	Thorthormi_3	4462	0.08	0.04	107.16
2009	Thorthormi_3	4462	0.10	0.02	22.38
1990	Thorthormi_4	4461	0.11		
2001	Thorthormi_4	4461	0.14	0.03	22.70
2007	Thorthormi_4	4459	0.14	0.01	5.25
2009	Thorthormi_4	4461	0.13	-0.02	-11.15
2001	Thorthormi_5	4461	0.05		
2007	Thorthormi_5	4461	0.05	0.00	5.34
2009	Thorthormi_5	4459	0.07	0.02	43.61
1990	Luggye	4459	0.98		
2001	Luggye	4459	1.16	0.18	18.45
2007	Luggye	4459	1.26	0.10	8.83
2009	Luggye	4459	1.41	0.15	12.00
1990	Drukchung	4706	0.14		
2001	Drukchung	4706	0.12	-0.01	**-10.14**
2007	Drukchung	4706	0.11	-0.01	**-7.97**
2009	Drukchung	4706	0.12	0.00	2.89
2001	Bechung	4337	0.06		
2007	Bechung	4337	0.11	0.05	73.80
2009	Bechung	4337	0.17	0.06	54.77

Table 4. Change of glacial lake per year

Year	Names of Lakes	Elevation (m)	Area		Perimeter	
			m²/year	km²/year	m/year	km/year
1990-2009	Bechung	4337	8680.18	0.009	-114.70	-0.115
	Rapstreng	4368	8493.37	0.008	132.75	0.133
	Thorthormi_1	4454	36119.06	**0.036**	231.60	0.232
	Thorthormi_2	4459	4642.96	0.005	65.42	0.065
	Thorthormi_3	4462	5104.93	0.005	96.06	0.096
	Thorthormi_4	4459	1664.90	0.002	4.42	0.004
	Thorthormi_5	4461	5985.88	0.006	160.90	0.161
	Luggye	4459	35581.19	**0.036**	390.75	0.39
	Drukchung	4706	-339.95	-0.0003	17.46	0.02

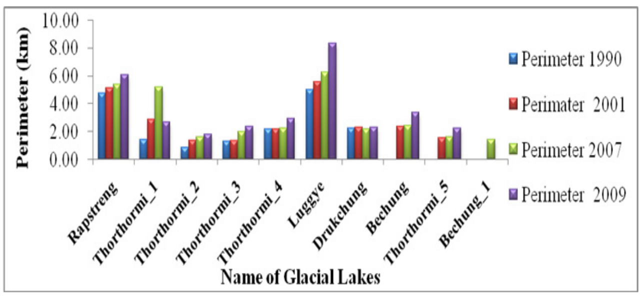

Figure 5. Perimeter of glacial lakes (1990-2009).

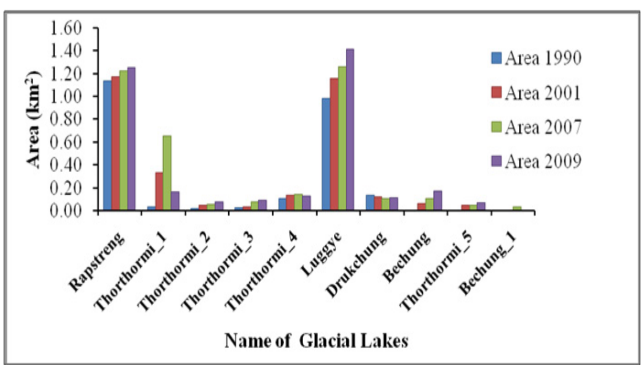

Figure 6. Area of glacial lake (1990-2009).

had taken the initiative for the mitigation jointly with the funding from Japan government.

5. Conclusions

Rapid retreat of glaciers during the past decade has caused fast accumulation of melt water resulting in the formation of glacial lakes at the toes of the glaciers, and increased the glacial lake volume and diminished the strength of the material damming with time. Eventually, there will be breaching of loose-moraine dam, resulting in a GLOF[11,22,39,40]. As it is found the retreat rate of this study area, the glaciers retreated from 15-35 m^{-1} year in general but it has been accelerated more from 2000 to 2009 although it is a shorter span of time.

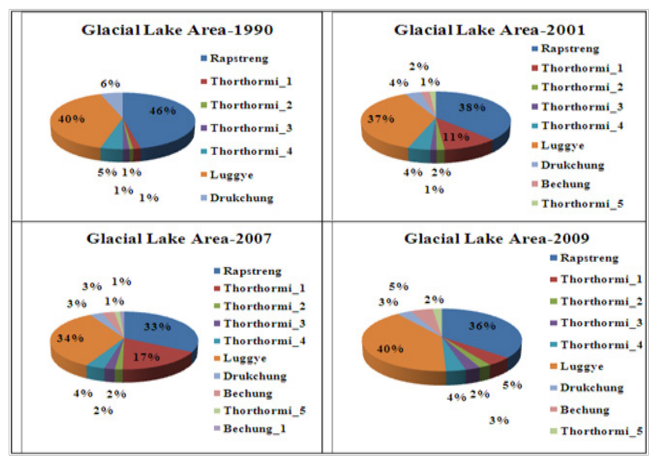

Figure 7. Area of glacial lake in percentage (%).

The recent rise in the glacier retreat and thinning has resulted in the ponding of new glacial lake of Bechung which was not been existed in 1990s. The gradual increase in debris over glacial lake coverage is expected to exert significant influence on the future response of these glaciers to climate change[41,42]. Over all the highest expansion rate of glacial lakes were Thorthormi-1 and Luggye around 0.036 km²/year and smallest were Thorthormi-2 and Thorthormi-3 around 0.005 km²/year.

Increasing glacial lakes may give rise to additional dangers in the near future, hence proper monitoring of glaciers is very essential for the water resources management and for the purposes of disaster mitigation of Bhutan. Mitigation measures have to be taken around the glacial lakes by studying the detail of surroundings and removing the loose stones which probably avalanche into the glacial lakes. A major challenge to this is the ability to accomplish this task as these areas are characterized by the rarefied atmosphere, high altitude and the remote locations.

6. Acknowledgements

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