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ORIGINAL ARTICLE

Glacier changes and related glacial lake expansion in the Bhutan Himalaya, 1990–2010

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Abstract This paper discusses the recent retreat of glaciers and the changes in supraglacial lakes in the Bhutan Himalaya during the last two decades. We calculated the changes in clean and debris-covered glaciers and the formation, disappearance, and expansion of glacial lakes during the beginning of 1990s, 2000s, and 2010 using Landsat TM and ETM+ images. For this purpose, eight river sub-basins namely Wang Chu, Chamkar Chu, Dangme Chu, Kuri Chu, Mangde Chu, Mo Chu, Pho Chu and Northern Basin were considered. A retreating trend was found in the case of clean glaciers. Debris-covered glaciers in this region were found to have undergone an increase of about 29 %, and this increase was partially contributed by those expanded upstream. This increase in the debris-covered area is higher on the southern side of the Bhutan Himalaya. It is found that a number of moraine-dammed glacial lakes were formed during this period and can be potentially dangerous depending on the size, distance from the glacier and altitude. Most of the glacial lake formation and expansion occurred on the southern side of the Bhutan Himalaya.

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Introduction

Mountain glaciers in the Eastern Himalayas are highly sensitive to climate change and hence are good indicators of climate change. It is predicted that the glaciers in high mountain Asia also will contribute to the future sea level rise due to rapid mass loss (Radić and Hock 2011). The Himalayan range is more than 2000 km long and extends from Afghanistan to Burma. With an exception of high-altitude, debris-covered glaciers in the Karakoram Himalaya (Hewitt 2005, 2007, 2011), glaciers in the Himalayas have shown a remarkable retreating trend towards the end of twentieth century (Dahe et al. 2000; Bajracharya et al. 2007; Bolch et al. 2012; Veettil et al. 2014). Many researchers believe that this rapid loss of glaciers in this region is due to the recent global warming (Bajracharya et al. 2007; Bolch et al. 2012). The term climate change must be used with caution, as the changes can be due to the precipitation or temperature variability. The anomalies in the precipitation and the temperature based on the $\delta^{18}O$ variations using ice-core records showed the evidence of climate change in the central Himalaya (Dahe et al. 2000). In the central Himalaya, the summer precipitation and the winter temperature control the annual variations in $\delta^{18}O$ (Dahe et al. 2000). In this region, the decadal variability in temperature and precipitation is significant compared with the interannual variability. The glacier retreat in the Himalayas may lead to the formation of moraine-dammed glacier lakes. Many of the glacial lakes in the Bhutan Himalaya were created/expanded during the last few decades (Komori 2008; Gardelle et al. 2011). About 9.4 % of

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the total glaciated area in Bhutan consisted of debris-covered glaciers in 1980s and is increased to 14 % in 2010s (Bajracharya et al. 2014). Glacial lakes can be supraglacial, englacial or subglacial (Benn and Evans 2010). Moraine-dammed lakes associated with the debris-covered glaciers can be potentially dangerous to communities and infrastructures (Quincey et al. 2007; Benn and Evans 2010). The retreat of glaciers, the formation of moraine-dammed lakes and the glacial lake outburst floods (GLOF) are major concerns in a high-altitude country like Bhutan, where the regional water supply and water for hydropower generation are originating from the glaciated mountains. Moraine dams in Nepal and Bhutan, consist of sand and gravel, are poorly covered with vegetation (Hambrey et al. 2008) and can reach up to hundred metres in height at the glacier margin (Benn and Evans 2010). GLOFs can be triggered by rock falls, ice avalanches, calving of ice cliffs (Hambrey et al. 2008), rainfall, snowmelt, thawing of ground ice or earthquakes. The stability of the moraine dam depends on the height-to-width ratio and porosity of the wall (Hambrey et al. 2008). The GLOFs (locally known as tschoscrup) recently reported in Bhutan include the Tarina Tso (1957), the Bachamancha Tso (1960), the Lugge Tsho (October 1994, killed 21 people due to moraine collapse) and the Tshojo Glacier flood (2009). It is important to monitor and evaluate the formation and expansion of glacial lakes in this area to prevent such incidents in the future.

Recently, remote sensing techniques have provided essential tools for the estimation of various glacier parameters such as area, equilibrium line and mass balance (Racoviteanu et al. 2009; Rabatel et al. 2012; Bajracharya et al. 2014; Veettil et al. 2014) and monitoring glacial lakes (Gardelle et al. 2011; Huggel et al. 2002). The objectives of this research include (1) mapping the glacier changes in the Bhutan Himalaya during the beginning of 1990s, 2000s and 2010s using multi-temporal satellite data, digital elevation models (DEM) and existing glacier inventories; (2) monitoring the formation, disappearance and expansion of glacial lakes in eight river basins in the Bhutan Himalaya; and (3) exploring the possibility of a teleconnection, if any, between the glacier retreat and the expansion of glacial lakes in the Bhutan Himalaya. In this study, we mapped clean and debris-covered glaciers separately because different techniques were utilized to calculate them.

Study area and climate conditions

Valley glaciers in the Himalayas may be long up to several kilometres and occupy more than 75 % of the total glaciated area (Sakai 2012). The Kingdom of Bhutan is a landlocked country in the eastern Himalayas in the Indian subcontinent and shares the political boundary with India, Nepal and China (Fig. 1a). Glaciers in Bhutan cover about 10 % of the land surface area (Fig. 1b). The first glacier observation in Bhutan was done in the 1960s (Gansser 1970), and there is no complete glacier inventory that exists yet. The altitude ranges from below 200 m asl to more than 7500 m asl. All mountain peaks above 5000 m asl in Bhutan are glaciated, and all glaciers in Bhutan are situated above 4000 m asl (Karma et al. 2003). From a glaciological point of view, geomorphology of high mountain Bhutan is similar to that of Nepal Himalayas. The highest peak in Bhutan, the Kulha Gangri, is having an altitude of 7544 m asl, and the second highest peak, the Chomo Lhari, has an altitude of 7314 m asl. It is reported that nearly 20 peaks are located above 7000 m asl in Bhutan, and the majority of them are situated in the Great Himalayan Range in the north. Inner Himalayas towards the south of Great Himalayan Range and the black mountains in the central Bhutan form a watershed between two major river systems in Bhutan—Mo Chu and Dangme Chu. With an exception of Amo Chu and Nyere Ama Chu, glaciers contribute to all rivers in Bhutan (Bajracharya et al. 2014). Major rivers in Bhutan are tributaries of Brahmaputra River in India. Glaciers in Bhutan were classified as´summer accumulation typé and the monsoon precipitation in the eastern Himalaya nurtures the glaciers in this region (Ageta and Higuchi 1984). This means that an increase in summer temperature promotes liquid precipitation (rain) and promotes glacier mass loss due to albedo reduction in the glacier surface. Compared to the Nepal Himalaya, the south-western monsoon precipitation dominates higher in the Bhutan Himalaya (Karma et al. 2003). Highest precipitation occurs during June–September, and the post-monsoon rain occurs during October–November. The dry season occurs during November–March. Mean annual precipitation varies from 500 mm in the northern region to 5500 mm in the southern foothills (ICIMOD 2001), and hence there is a high north-to-south gradient in precipitation in Bhutan. There is a strong west-to-east gradient in precipitation as well, and the monthly mean precipitation increases from the west to the east along the Bhutan Himalaya (Fig. 1c). The climatological divisions in Bhutan are the southern foothills (subtropical), the middle valleys or inner hills (temperate) and the northern region (alpine) (ICIMOD 2001).

We calculated the glaciated area (both clean and debris-covered) and the formation, disappearance and expansion of glacial lakes in the Bhutan Himalaya (89°92 12′–92°00′E, 27°36′–28°93 30′N) during the beginning of 1990s, 2000s and 2010s. For convenience, we divided the study areas into eight river sub-basins in the Bhutan Himalaya namely Wang Chu, Chamkar Chu, Dangme Chu, Kuri Chu, Mangde Chu, Mo Chu, Pho Chu and the

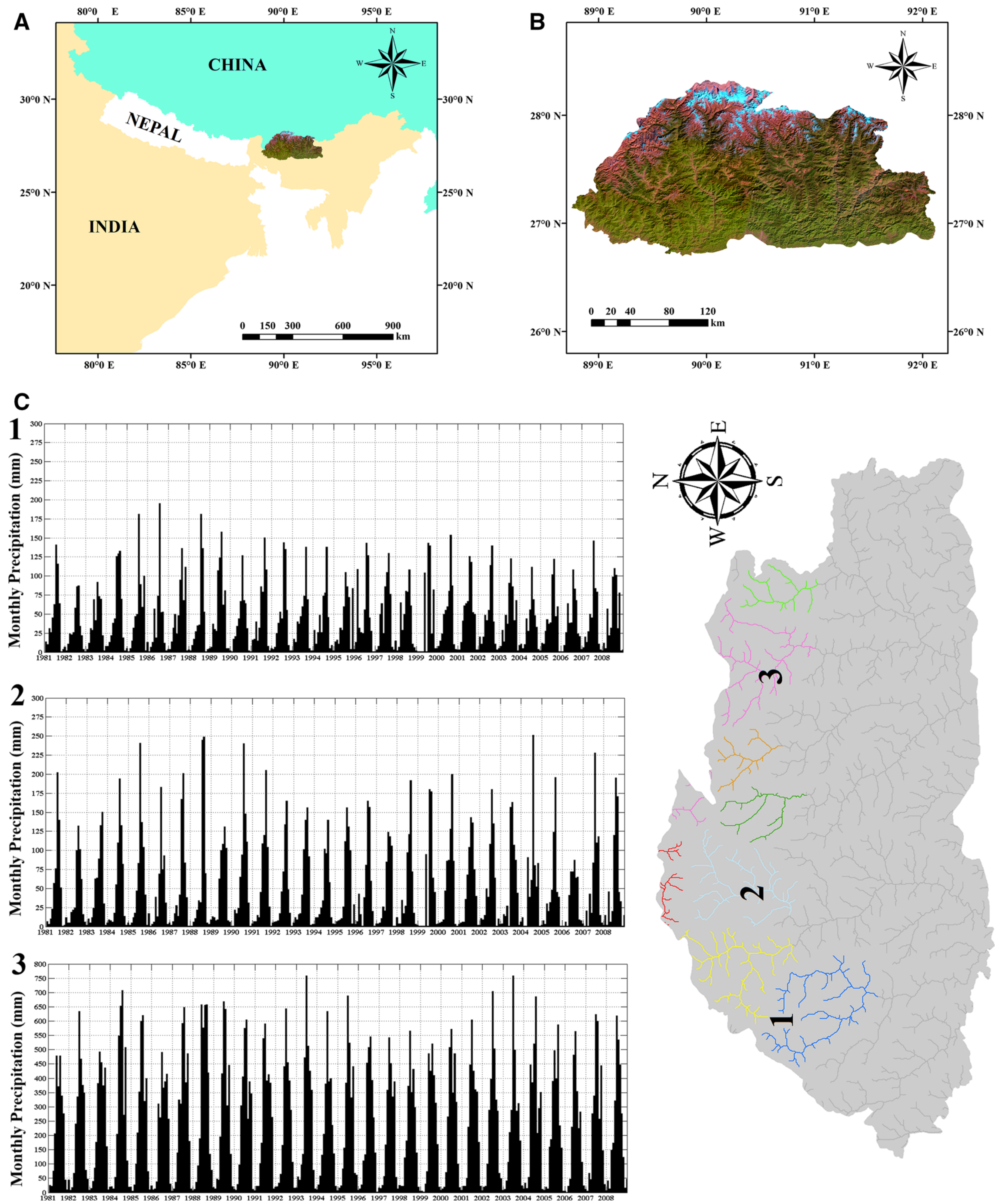

Fig. 1 **a** Geographical location of Bhutan. **b** Land cover of Bhutan (5-4-3 Landsat false-colour composite). **c** The west-to-east precipitation gradient in the Bhutan Himalaya

Northern Basin (Fig. 2). Some of the potentially dangerous and large glacial lakes such as Lugge Tsho and Zanam Tsho are situated in Pho Chu and Mangde Chu basins, respectively. In order to foresee future GLOF-related accidents, it is important to apply the available techniques to evaluate the tendencies in the glacier mass loss and the formation and expansion of glacial lakes in this region.

Datasets

We used Landsat series of images (TM and ETM+) for monitoring glaciers and glacial lakes in Bhutan. Despite the medium resolution in the visible and infrared channels (30 m, except thermal), Landsat images cover all the glaciers in the Kingdom of Bhutan and are freely available

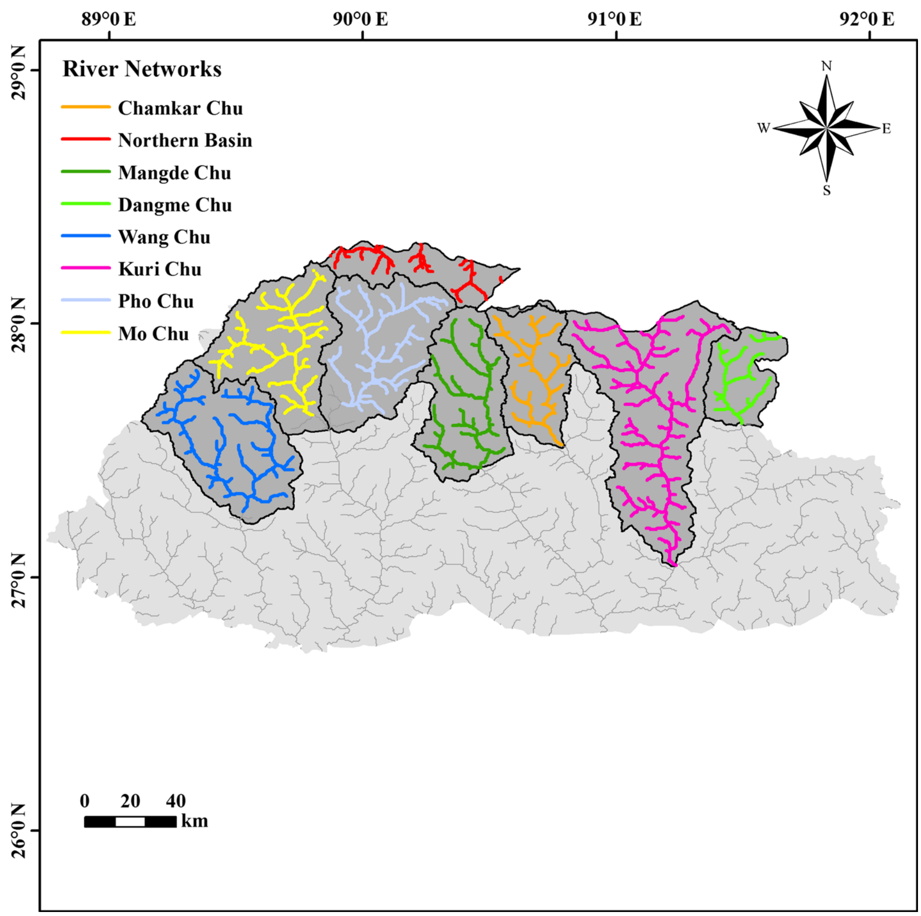

Fig. 2 Major river networks in Bhutan and the eight river basins considered in this study

from USGS (http://earthexplorer.usgs.gov/). Landsat images from USGS were already radiometrically and geographically corrected. In order to ensure visual quality and accuracy in mapping, only cloud-free images taken during September–January were used in this research. If available, the best images are those acquired during November–February because the glacier margins will not covered by fresh snow, and this makes the delineation of the glacier boundary easier. The details of the images used in this research are given in Table 1. We used three mosaics of the study site, one during the early 1990s, one in 2000 and another during the early 2010s. For mapping debris-covered glaciers in the study area, DEM are necessary and for this purpose, we used ASTER GDEM that is having a spatial resolution of 30 m and a vertical accuracy of 20 m. SRTM DEMs were not used because the C band penetrates into snow and causes error in the elevation measurements. All the images were processed using Erdas IMAGINE and ArcGIS software packages. We also used GLIMS Randolph Glacier Inventory for comparison purposes.

Methodology and results

Glacier mapping in the Bhutan Himalaya was done in two steps using Landsat TM and ETM+ images. The boundary used in this research was created before 2007 as political boundary has no meaning in terms of glaciological analysis (new boundary is created by National Land Commission, Bhutan, in 2007). In the first step, clean glaciers were mapped using satellite images, and this process is fully automatic except in the case of cast shadows. In the second step, debris-covered glaciers were mapped using a semi-automatic approach based on Paul et al. (2004). Only cloud-free images acquired during the dry season (September–January) were used in this study to reduce tedious manual editing due to excess snow cover and compare with other images. We used three or four images for creating the required mosaics of Landsat TM and ETM+ images for 1990s, 2000s and 2010s. We compared the results with already available glacier inventories such as the GLIMS Randolph glacier inventory (RGI version

Table 1 Details of the images used in this study

Decade	Date of acquisition	Sensor	Spatial resolution (m)	Path/row	Scene/product ID
1990s	1991 November 01	Landsat TM	30 (VNIR), 120 (thermal)	138/40	LT51380401991305ISP00
	1991 November 01	Landsat TM	30 (VNIR), 120 (thermal)	138/41	LT51380411991305ISP00
	1988 September 14	Landsat TM	30 (VNIR), 120 (thermal)	137/41	LT51370411988258BKT0
2000s	2000 December 26	Landsat ETM+	30 (VNIR), 60 (thermal), 15 (PAN)	139/41	LE71390412000361SGS00
	2000 November 17	Landsat ETM+	30 (VNIR), 60 (thermal), 15 (PAN)	138/40	LE71380402000322SGS00
	2000 December 19	Landsat ETM+	30 (VNIR), 60 (thermal), 15 (PAN)	138/41	LE71380412000354SGS01
	2000 December 28	Landsat ETM+	30 (VNIR), 60 (thermal), 15 (PAN)	137/41	LE71370412000363SGS00
2010s	2010 January 21	Landsat TM	30 (VNIR), 120 (thermal)	138/40	LT51380402010021KHC00
	2010 January 21	Landsat TM	30 (VNIR), 120 (thermal)	138/41	LT51380412010021KHC00
	2011 September 30	Landsat TM	30 (VNIR), 120 (thermal)	137/41	LT51370412011273KHC00

3.2). Finally, we mapped the glacial lakes within eight river basins in Bhutan (Wang Chu, Chamkar Chu, Dangme Chu, Kuri Chu, Mangde Chu, Mo Chu, Pho Chu and Northern Basin). These glacial lakes were classified as major lakes if the area is greater than 0.02 km^2 (Bajracharya and Mool 2009).

Glacier mapping in the Bhutan Himalaya during 1990–2010

For mapping clean glaciers, we calculated normalized difference snow indices (NDSI = [TM2 − TM5]/[TM2 + TM5]) and applied a threshold (usually 0.4–0.6). Before calculating the indices, DN values in all the wavelengths used were first converted into radiance and then to the corresponding surface reflectance values. The selection of threshold values depends on the presence of shadows, local atmospheric conditions and even the date of acquisition of the images. We used a threshold value of 0.42 and then subtracted the vegetation using normalized difference vegetation index (NDVI = [TM4 − TM3]/[TM4 + TM3]) images and water bodies using normalized difference water index (NDWI = [TM4 − TM1]/[TM4 + TM1]). Some manual editing is required because the Bhutan Himalaya consists of many frozen glacial lakes, and ratio images are sensitive to such conditions (Racoviteanu et al. 2009). In the case of cast shadows, we compared the results obtained from other mosaics of the same period and edited manually. Figure 3 shows the changes in clean glaciers during 1990–2010 in the five river basins namely Mangde Chu, Mo Chu, Pho Chu, Chamkar Chu and Northern Basin, where major mass loss has occurred during this period.

Without mapping the debris-covered glaciers, glacier area calculations will be incomplete. The difficulty in mapping the debris-covered glaciers using remote sensing originates from the similarity between the spectral response of supraglacial debris and nearby moraine deposits. In order to discriminate the supraglacial debris from other land surface features, several approaches were developed by researchers such as using DEMs (Paul et al. 2004; Veettil 2012; Veettil et al. 2014) and using thermal bands (Shukla et al. 2010). In this research, debris-covered glaciers were mapped using the semi-automatic glacier mapping based on Paul et al. (2004) and later followed by Veettil (2012). Firstly, a thresholded ratio image (TM4/TM5 > 2.0) is created to separate clean glacier and snow from other objects. Secondly, the thresholded hue component of the intensity–hue–saturation transformation of composite of TM bands 3, 4 and 5 (hue > 126) is calculated to separate vegetation and vegetation-free areas. Finally, a slope image is calculated and applied a threshold (<15°) because the debris will not stay on slopes higher than this value (Paul et al. 2004). The overlay of the above three binary maps gives the debris-covered glacier maps. Figure 4 shows the changes in debris-covered glaciers in four riven basins (Mangde Chu, Mo Chu, Pho Chu, Chamkar Chu), where the majority of the changes has occurred.

The discrimination between snow/ice and rocks using TM channels 5 (1.55–1.75 µm), 4 (0.76–0.9 µm) and 2 (0.52–0.60 µm) is an easier task compared with differentiation between snow on ice and snow on soil (Arnaud et al. 2001). Exceptional snowfall may affect the accuracy of clean glacier boundary. The changes in glaciated areas over the last two decades are given in Table 2. It is found that the area covered by clean glaciers has been decreased by about 37 % during 1990–2010. The upstream increase in the area of debris-covered glaciers can be partially due to the loss of clean glaciers above the debris-covered glaciers, and the underlying debris cover became exposed. Artefacts in the DEM used may increase the number of errors in mapping debris-covered glaciers in the case of steep mountain relief, but for debris-covered glacier

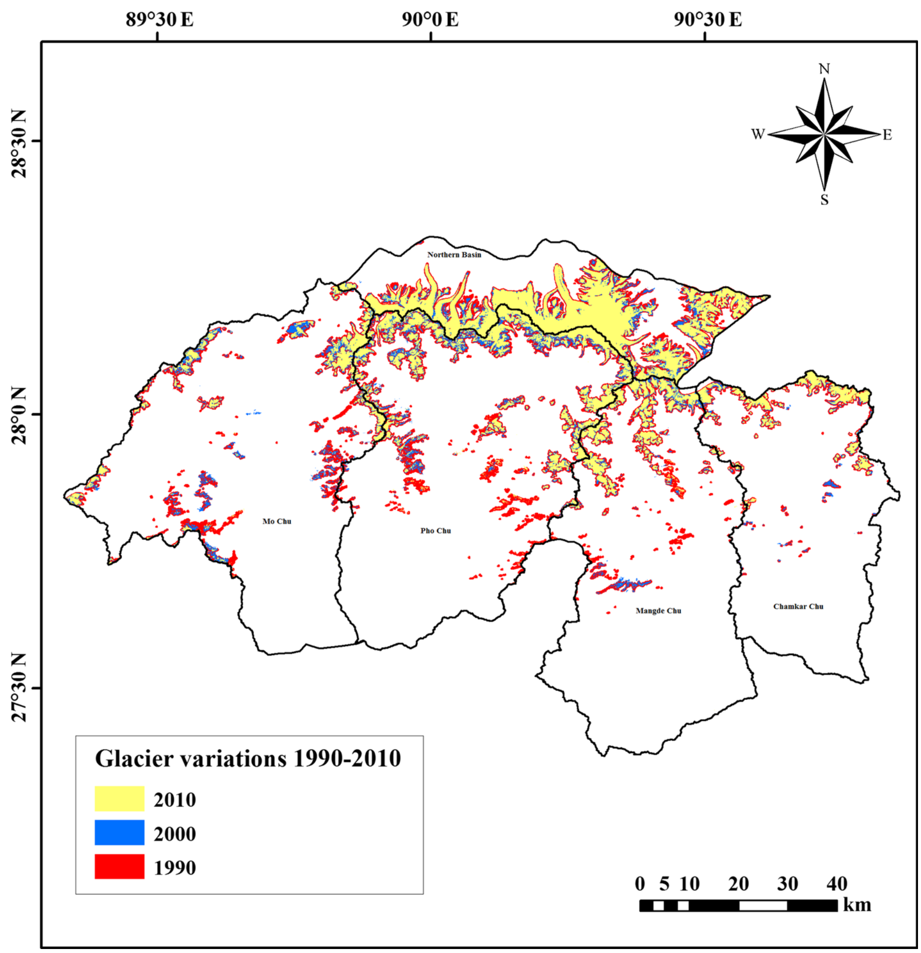

Fig. 3 Major changes in clean glaciers in the Bhutan Himalaya during 1990–2010 in the Mo Chu, Pho Chu, Mangde Chu, Chamkar Chu and the Northern Basin

tongues in gentle slopes, this method is widely used (Paul et al. 2004). There is an upstream increase of about 28.9 % in the area of debris-mantled glaciers during 1990–2010, partly contributed by the decrease in snow cover and mass loss of clean glaciers. The overall decrease in the total glaciated area is found to be 22.56 %. The trend in the glacier changes was similar to that observed by Bajracharya et al. (2014). However, there is a difference of 13.9 % higher than reported by Bajracharya et al. (2014) in the case of total glaciated area. This can be due to the following reasons. (1) We used the national boundary of Bhutan before 2007, which means that a few glaciers within the Chinese political boundary are covered in this research (97.28 km^2 clean glaciers and 16.14 km^2 debris-covered glaciers in 2010), in order to include more glaciated area in the research focus. (2) The date of acquisition of the images used for the above-mentioned study are not given by the authors, and we assume that some differences may arise due to different date of acquisition of the images, and we used the one with least snow cover in order to avoid misclassification of temporary snow as glacier.

Mapping glacial lakes during 1990–2010

Current studies on glacial lakes using remote sensing include false-colour composite images from multispectral images, water indices and reclassification ramp tables (Xin et al. 2012). Fully automatic mapping of lakes were not used in this research because most of them are normally frozen or turbid or proglacial lakes at very high altitudes, and hence poor results are normally expected. Some of the lakes monitored using NDWI images (Huggel et al. 2002) were added manually to improve the lake margins. High absorption of infrared wavelengths (0.8–2.5 μm) and reflection of visible wavelengths (blue wavelength in particular) by water are utilized for calculating the NDWI. These NDWI images were applied a threshold value between −0.58 to −0.62 to get glacial lake outline (Huggel et al. 2002) and further compared with Google Earth images. The number of coalesced and disappeared lakes, changes in the number of lakes and area over the last three decades are given in Table 3. Moreover, glacial lakes were grouped based on the elevation, area and the number of lakes under this classification as given in Table 4.

Fig. 4 Major changes in debris-covered glaciers in the Bhutan Himalaya during 1990–2010 in the Mo Chu, Pho Chu, Mangde Chu and the Chamkar Chu basins

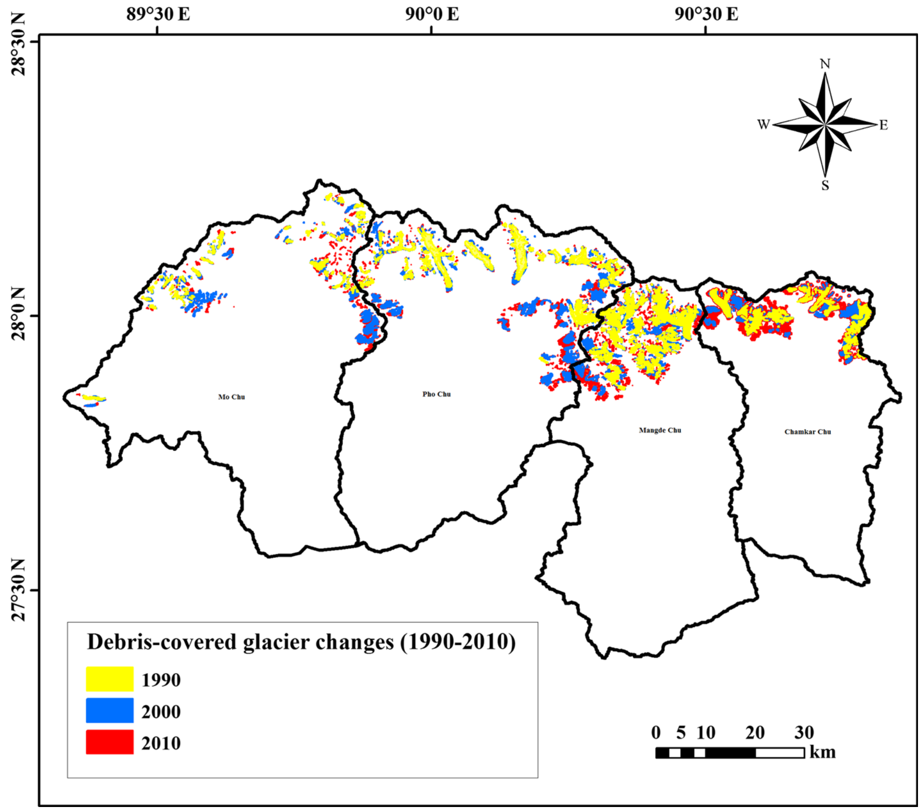

Table 2 Glacier changes from 1990 to 2010

Year	Glacier area (km^2)			Changes in glacier area (%)		
	Clean glacier	Debris-covered Glacier	Total	Clean glacier	Debris-covered Glacier	Total
1990	1344.8	198.2	1543			
2000	1221.4	253.3	1474.7	−10.1	21.7	−4.6
2010	980	278.9	1258.9	−24.6	9.2	−17.1
1990–2010				−37.2	28.9	−22.5

It is seen from the results that the number of glacial lakes have been increased in number and area during the past two decades in some basins (Fig. 5) particularly in the southern sides of the Bhutan Himalaya. Many of the glacial lakes are found to be formed or expanded at the terminus of larger debris-covered glaciers. Small glacial lakes formed near the terminus later coalesce to form larger lakes in basins such as Pho Chu and Mangde Chu (Sakai 2012) and thus increase its potential to form a GLOF. Retreat of clean glaciers also resulted in the formation and expansion of glacial lakes, mostly in Chamkar Chu, Kuri Chu, Northern Basin, Mo Chu and Mangde Chu basins. In these regions, lake formation and expansion is direct. It is noticed that many lakes near clean glaciers are either being expanded due to continuous mass loss or being dried up due to less supply of melt water, increased evaporation, infilling by sediments or a change in glacier dynamics. Many supra-glacial lakes on debris-covered glaciers were expanded by coalescing smaller lakes, ice melting under debris cover and marginal debris falling into lakes. Major glacial lakes are defined as having an area of 0.02 km^2 or more (Bajracharya and Mool 2009). Most of the glacial lakes are located between 4500 to 5000 m asl and are having an area between 0.01 to 0.1 km^2.

Discussion and conclusions

The mapping of decadal glacier changes in the Bhutan Himalaya is made possible by the availability of Landsat series of images. Since we used a compilation of images every decade, it was possible to get a more accurate glacier maps compared with the existing inventories. The accuracy of the glacier maps using satellite images depends on the spatial resolution of the images used, seasonal variations in

Table 3 Lake changes from 1990 to 2010

Year	Northern Basin	Wang Chu	Mo Chu	Pho Chu	Mangde Chu	Chamkar Chu	Dangme Chu	Kuri Chu
Number of glacial lakes								
1990	14	24	126	260	185	164	31	199
2000	22	31	135	253	190	162	31	188
2010	31	26	142	263	200	182	34	188
Area covered by glacial lakes (km^2)								
1990	10.07	0.98	4.51	16.38	12.75	9.87	2.07	9.05
2000	10.44	1.29	6.12	20.89	15.68	12.84	2.30	10.17
2010	11.85	1.29	5.84	20.86	15.19	12.57	2.39	11.15
Number of coalesced lakes (from lakes as in 1990)								
2000	0	0	3	18	7	0	0	10
2010	0	0	3	25	7	1	0	12
Number of disappeared lakes (from lakes as in 1990)								
2000	0	1	0	8	0	6	0	5
2010	0	7	0	18	1	7	0	7
Number of newly formed/identified lakes								
2000	8	2	12	19	13	3	0	4
2010	11	3	8	32	10	23	3	5

Table 4 Lakes classified based on altitude and area

Basin	Number of lakes									
	Altitude					Area				
	<4500	4500–5000	5000–5500	5500–6000	>6000	<0.01	0.01–0.1	0.1–0.5	0.5–1	>1
Northern Basin	0	1	21	8	1	8	14	4	1	4
Wang Chu	11	13	2	0	0	7	16	3	0	0
Mo Chu	40	69	34	0	0	35	95	13	0	0
Pho Chu	42	100	120	0	0	54	155	46	5	2
Mangde Chu	0	61	138	0	0	53	110	31	4	1
Chamkar Chu	4	75	103	0	0	34	89	31	27	1
Dangme Chu	4	29	1	0	0	10	18	6	0	0
Kuri Chu	34	131	19	4	0	54	103	30	1	0
	135	479	438	12	1	255	600	164	38	8

snow and cloud cover (Bajracharya et al. 2014), and in the case of high-ablation season, it is difficult to estimate the glacier terminus (both clean and debris-covered). Since only cloud-free images are used and images acquired during high-ablation and snowfall seasons are omitted, the remaining question is on the spatial resolution. To minimize the misclassification of excess snow as glacier, we compared our results with Google images, which are having a very high spatial resolution. Systematic biases of the DEM always add some errors in the calculation of area of the debris-covered glaciers. The changes in the debris-covered glaciers are important in analysing the climate change impacts, though the changes in the terminus of these glaciers do not represent a direct glacier response to climate change (Sakai 2012). This can be due to the differences in the debris thickness and its influence on glacier melting underneath or calving from the glacier front into the lakes. However, for analysing a GLOF, considering debris-covered glaciers is important. In the Bhutan Himalaya, most of the new lakes formed are on the supraglacial debris cover, and the area of debris-covered glaciers has been increased by 28.92 % from 1990s to 2010s. This increase in the debris-covered glaciers was partially contributed by the upstream expansion as well. The calculated

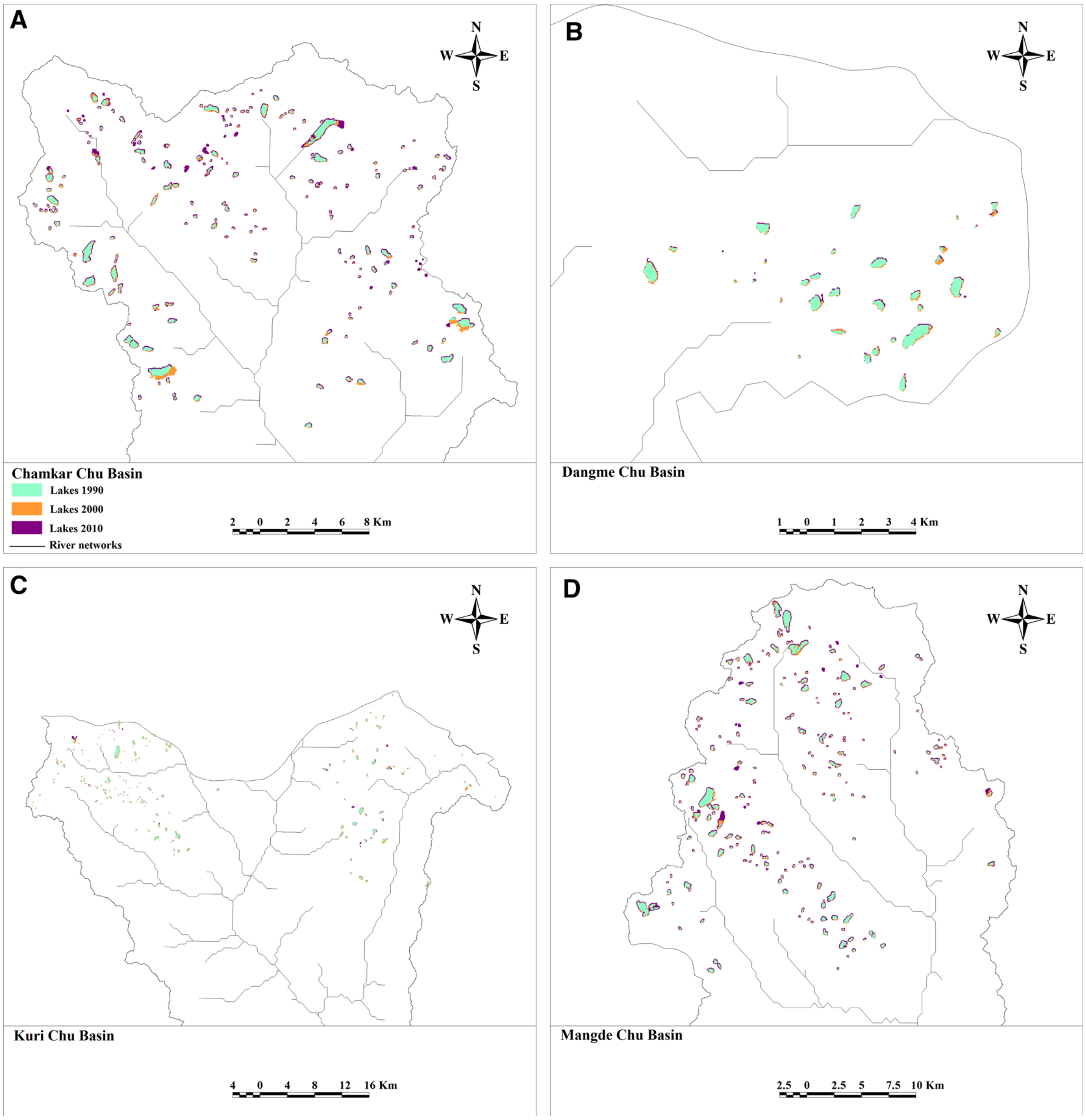

Fig. 5 Changes in glacial lakes in eight river basins (Chamkar Chu, Dangme Chu, Kuri Chu, Mangde Chu, Mo Chu, Northern Basin, Pho Chu and Wang Chu) in the Bhutan Himalaya (1990–2010)

total area of glaciers in 2000s (1474.728 km^2) from this study is more than that calculated by Karma et al. (2003) and ICIMOD (2001) (1316.73 km^2), which was within the same national boundary used in this research. This can be partly because there were no efficient mapping methods to calculate debris-covered glaciers before Paul et al. (2004) and that some of the debris-covered glaciers calculated here were previously classified as ice. Other errors can include those due to image cloud cover and DEM artefacts. Possible triggers of GLOFs include dam collapse, melting ice, seepage, dam overflow, rock fall, debris flow, ice avalanche and ice calving. A considerable decrease in the area of clean glaciers and an increase in the area debris-covered glaciers were found in the four basins namely Mo Chu, Pho Chu, Mangde Chu and Chamkar Chu. Interestingly, high rate of increase in the area of glacial lakes has occurred in these basins (Mo Chu: 23 %; Pho Chu: 21.5 %; Mangde Chu: 16.5 %; Chamkar Chu: 22 %).

We compared our results of the glacial lake inventory with that created using ALOS PRISM data that are having a better resolution that Landsat data by Tadono et al. (2012) and Ukita et al. (2011). Tadono et al. (2012) studied the glacial lakes in the Mangde Chu basin, and the latter one gives the details of glacial lakes in the four sub-basins (Mo Chu, Pho Chu, Mangde Chu and Dangme Chu). Some of the lakes in these studies could not map (because of

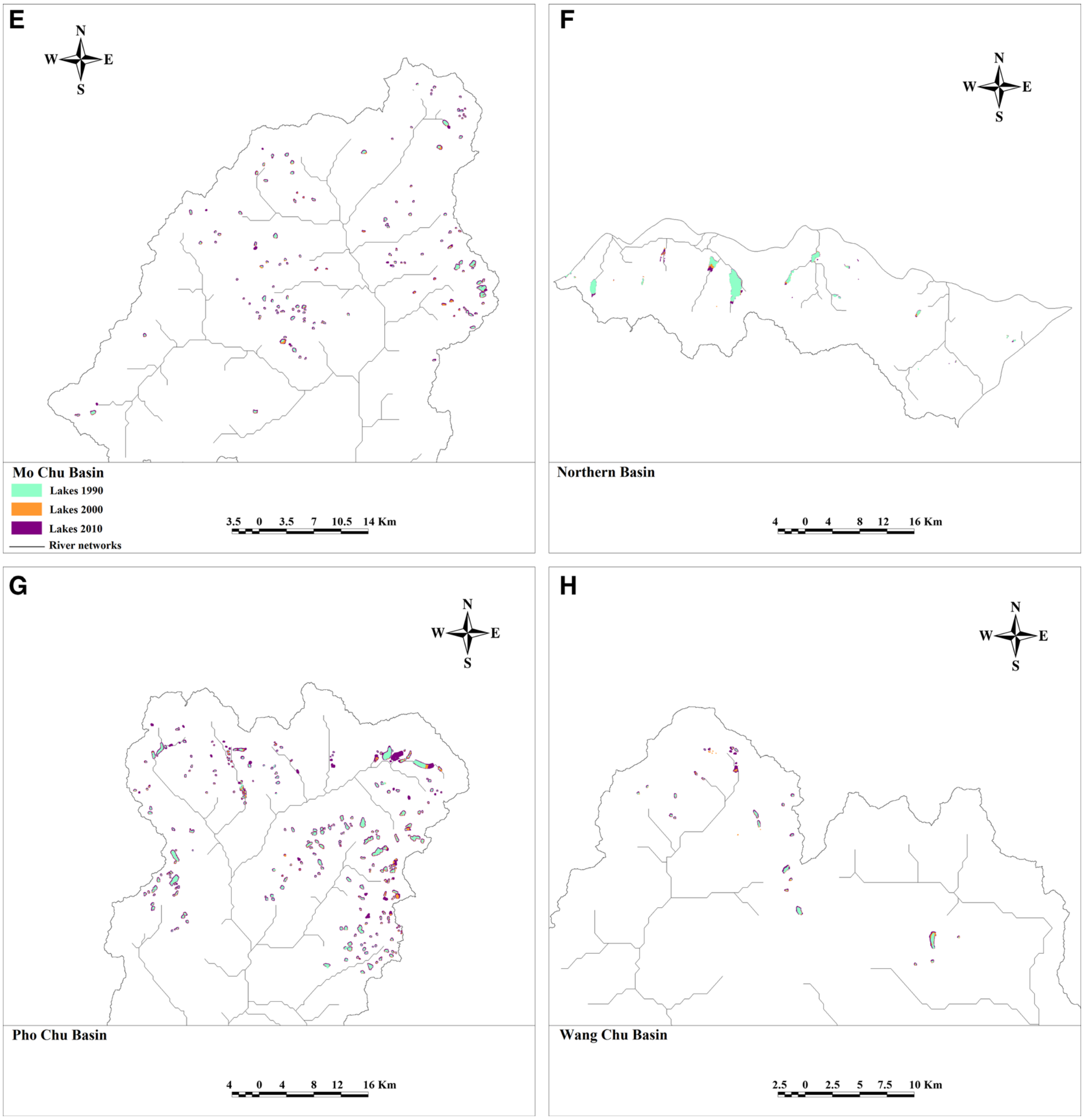

Fig. 5 continued

frozen lakes at the time of image acquisition). Moreover, we did not have the high-resolution images like ALOS PRISM data for a long time (ALOS was launched on January 24, 2006), or some existing high-resolution images were not available for the scientific community (Corona and KH-9 Hexagon, for example) to calculate the evolution of glacial lakes in the study site. Other studies on glacial lake analysis in Bhutan include Ageta et al. (2000) which could successfully classify glacial lakes based on location and mode of formation. The lake inventory in our research can be considered as more complete because it covers all river basins in the glaciated parts of the Bhutan Himalaya. In addition, due to manual correction and comparison with other lake inventories, this study gives better results compared with fully automatic mapping of glacial lakes using Landsat images. The drawbacks include not using bathymetry data in this study, and only the areal expansion glacial lake glacial lake, not volume, is considered here. The presence of frozen lakes often causes difficulty in mapping glacial lakes, and this problem can be overcome by using a compilation of multispectral images of the same precipitation season and manual editing.

Lake area, volume and degradation of the moraine are some of the factors that determine the quantity of water available for an outburst and the growth of a moraine-dammed lake indicates the potential to form GLOF, which causes loss of life as well as infrastructures. Width-to-depth ratio of the moraine dam determines the hydrostatic pressure which causes bursting the wall and causes GLOF (Richardson and Reynolds 2000). Due to the erosion of moraine, a large quantity of unconsolidated sediments/tills can be entrained. GLOF can transport large amount of sediments due to high discharge rates (Richardson and Reynolds 2000) thereby bulking them and changing the flow dynamics accordingly. The two main modes of moraine-dammed lake evolution can be proglacial or supraglacial in origin. The first one is mostly associated with steep glaciers and water is collected behind the moraines. The latter develops on the glacier surface itself and is normally developed on debris-covered valley glaciers (Gardelle et al. 2011). Three-stage evolution of moraine-dammed lakes includes supraglacial pond formation, lake expansion and breaching of moraine dam (Hambrey et al. 2008; Benn et al. 2012). However, lakes can develop at the sides of glaciers, where water is often trapped behind the lateral moraine (and not begin as a supraglacial pond). It is observed that most of the supraglacial lakes in the study area were formed as small melt ponds and later expanded to become larger ones. The expansion and formation of supraglacial lakes on debris-covered glaciers are more complex. Ablation decreases towards the terminus due to the thick debris cover. At higher altitudes, ablation is less and thus glacial lakes form somewhere between the terminus and the equilibrium line.

Measurement of danger of glacial lakes can be approximately done based on the relative elevation from the base of the surrounding moraines to the lake surface (Sakai 2012), surface area, depth, distance to glacier and so on. Some of the glacial lakes, particularly in the Pho Chu basin, containing small islets were found to be disappeared recently (these islets were considered while calculating the lake area in this study). It is assumed that the disappearance of these islets can be due to the melting of ice under thin debris mantle (Sakai 2012). Some of the main causes of a moraine-dammed glacial lake failure are heavy melting of the parent glacier, the parent glacier sliding into the lake and seepage expansion. The expansion of glacial lakes on the southern side of the Bhutan Himalaya, particularly on debris-mantled glaciers, was found to be faster than on the northern side and the results supports the findings by Komori (2008). This observation is confirmed by the expansion of glacial lakes in the river basins like Pho Chu, Mo Chu, Mangde Chu and Chamkar Chu (see Fig. 5). Other than the change in temperature and precipitation, differences in wind speed can also influence the rate of expansion of glacial lakes (Yamada 1998; Sakai 2012). Glacial lake formation in the Bhutan Himalaya is higher at parts of glacier inclined less than 2° (Reynolds 2000), and this indicates that the glacial lake expansion is higher when ice flux from upstream is small (Sakai 2012). In addition, when the difference in relative height between the glacier surface and lateral moraine ridges are higher, supraglacial lakes can be larger (Sakai and Fujita 2010; Sakai 2012). Recent increase in the summer precipitation (monsoon) accelerated the mass loss of glaciers of summer accumulation type in the eastern Himalayas. However, this must be dealt with care because the precipitation is highly dependent on elevation in this region, and the precipitation is not uniform along the latitude or longitude in Bhutan. Expansion of glacial lakes not only causes economic loss due to GLOF but imbalances in the environment as well. Nearly 30 glacial lakes were classified into potentially dangerous lakes in this study based on their area, altitude and distance (buffer of 500 m) from the glacier. Sophisticated real-time monitoring systems and satellite images can be utilized effectively to prevent catastrophe due to GLOF in the Bhutan Himalaya.

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