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Glaciers Shrinking in Nepal Himalaya

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1. Introduction

Glaciers are repositories of information for climate change studies, as they are sensitive to global temperature and precipitation changes. Due to global warming the impact was directly influencing in the melting of the glaciers and enhancing in recent decades. The rapid melting of glaciers reduce the glacier area by which the glaciers are fragmented with increase in glacier number (Bajracharya et al., 2006a,b, 2007a,b, 2008, 2009a). The history of glacier study in Nepal is not old, it was just started by Fritz Műller in 1956; who visit Nepal as a participant in the Swiss Everest Expedition. During following years, the number of scientific expeditions has gradually increased. However, Nepal has no glaciers under long-term observation, though a number of fragmented and short studies have been made on the AX010 Glacier, Mera Glacier, Yala Glacier and Rikha Samba Glacier. The AX010 has the densest observations in terms of Glacier extent, mass balance, and ice flow (Fujita et al., 2001). The systematic investigation of glaciers in Nepal was first organized by Nagoya and Kyoto Universities of Japan. The Glaciological Expedition of Nepal (GEN), led by Higuchi (1976, 1977, 1978, 1980), carried out a series of field studies in coordination with Department of Hydrology and Meteorology (DHM) Nepal. The first detailed study of AX010 glacier was conducted in 1978/1979 (Ageta et al., 1980, 1992; Kadota et al., 1997), Yala Glacier was studied since the 1980s, and Rikha Samba Glacier has been surveyed intermittently since 1974 (Nakawo et al., 1976; Fugii et al., 1996; Fugita et al., 1997). The glaciers of Nepal was first mapped by ICIMOD in 2001 from the Indian Survey topographic maps published from 1963 to 1982. The maps were prepared from the aerial photographs of 1957 to 1959 with extensive field work (Mool et al.; 2001, 2005). The study revealed 3,252 glaciers with 5,323km^2 glacier area, which is almost 3.6% of the total land cover of Nepal. The second generation of glacier mapping of Nepal (Bajracharya et al., 2011 unpub.) was based on the satellite images of 2008/2009, which shows that the number of glacier has apparently increased but the total area has decreased drastically. The total number of glaciers in this survey shows 3808 glaciers with 4212km^2 glacier area and 346km^3 estimated ice reserves. The glacier area loss is about 20% in last 40 years. The glacier cover of Nepal reduces to 2.9% of total land cover in Nepal. The subsidence of glacier surface by 0.40m per year in Dudh Koshi basin is also reported since late 1960's due to the melting of the glaciers (Bolch, 2008). Bajracharya et al., 2008 has also reported the glacier retreat rate of 10 to 60m per year in Dudh Koshi basin. GEN, 2006 has studied many glaciers and reported the glacier retreat with different rate. The monitoring of glaciers in the high altitude of remote area with harsh climatic condition is thorny and cumbersome, hence; remote sensing approach is the best way of monitoring in the first round for the prioritization of detail mass balance study. The aim of the present study is to show the suitability of multi-temporal optical remote sensing data to map and monitor the glaciers and to illustrate the glacier retreat from different elevations. Moreover, the accuracy of multi-temporal Landsat data is addressed.

2. Study area

Nepal is one of the small, mountainous and landlocked South Asian countries extending between 26° 15′ to 30° 30′ N latitude and 80° 00′ to 88° 15′ E longitude (Fig. 1). The country's total area is 147,181km^2 and its length is 840km. The width of the country ranges from 90 to 230km (about 180km in average) from east to west.

Fig. 1. Location map of Nepal

It is bordered by massive countries, Tibet/China to the north and on the remaining three sides by India. The northern border runs along the crown of glaciated and snowy peaks with flat terrain to the southern border. The country has a great altitudinal variation ranging from 64m asl in the southeast to 8850m asl (Mt. Everest) in the north within the range of 150km, the greatest land-based relief in the world. The country is vulnerable to various hazards due to great elevation differences, fragile geological conditions, soft soil cover, steep river gradients and high intensity rainfall especially during the summer monsoon. An excessive monsoon rainfall usually triggers a variety of slope movements in Nepal often causing extensive damages to life and property.

3. Data and methods

3.1 Data

Landsat 7 ETM+

Glaciers show different spectral reflectance, which helps characterize them in satellite data to delineate glacier outline. The Landsat 7-ETM+ are freely downloadable and suitable for glacier mapping and monitoring. The Landsat images of 2008 and 2009 with least snow cover and no cloud cover were selected and acquired. The SLC-off was corrected with two images either SLC-off and SLC-on images or both cases the SLC-off images in which gaps is overlap each other from the Landsat Gapfill tools in the ENVI software.

Digital Elevation Model (DEM)

The glacier outlines when combined with a digital elevation model (DEM) to derive glacier parameters such as hypsometry, slope and elevation of crown and snout of the glaciers. The Shuttle Radar Topography Mission (SRTM) of 90m resolution data is used to derive the glacier parameters.

3.2 Methods

The methodology of semi-automated mapping of glaciers (Bajracharya et al., 2009 unpub.) is used to delineate the glacier boundary. The GLIMS ID is given to each one of the glacier polygons and the glacier attribute parameters were generated by combining the earth observation data and digital elevation model using GIS techniques.

The spectral uniqueness of glacier ice in the visible and near infrared (NIR) bands of the electromagnetic spectrum enables use of simple algorithms permitting semi-automatic mapping of glaciers (Frauenfelder et al., 2009; Paul, 2000), in contrast to a tedious fully manual approach. Among Clean ice type (CI-type) and Debris covered (DC-type) glaciers latter poses challenges in illuminating errors due to effect from surrounding materials. The threshold value of algorithm differs slightly in different scenes of the images. Bearing in mind the spatial scalability of features of interest, multi-band Landsat images enable extraction of information by standardized, uniform processing steps. The approach in mapping of CI-type and DC-type glaciers is different (Fig.2). The threshold value of NDSII for CI-type and mean slope for DC-type ideally maps all glacier pixels; further filtering using different variables such as NDVI (for vegetation), land & water mask (water bodies), mean hue, mean slope and mean altitude (glaciers), and then ultimately omitting polygons with areas less than 0.02 Km², eliminates most misclassified pixels and efficiently generates a product suitable for manual editing.

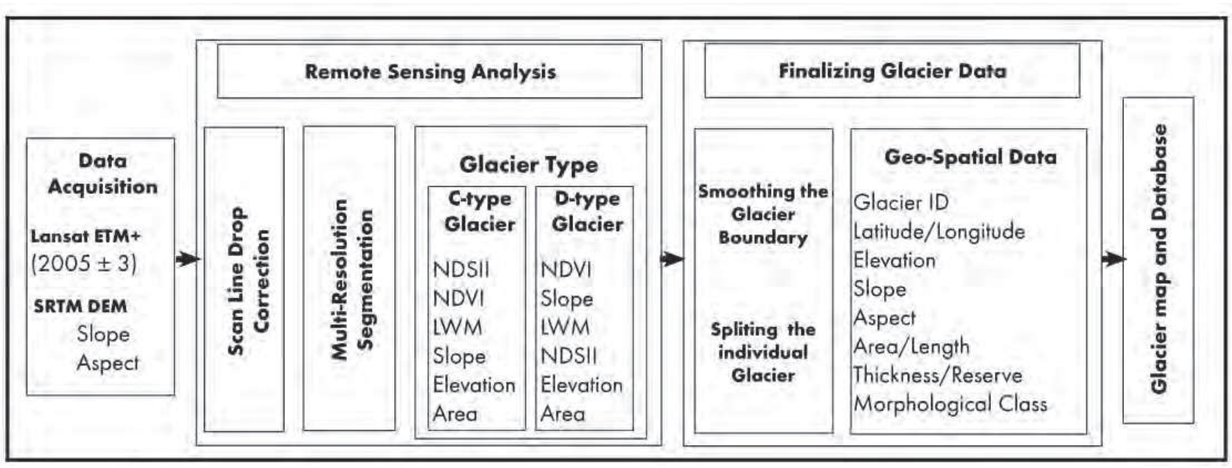


Fig. 2. Flow diagram of methodology for mapping of Clean Ice and Debris Cover glaciers using satellite images

4. Results

Altogether 3808 glaciers were mapped from Nepal. The total aerial extension of glaciers in Nepal is 4212km^2 with an estimated ice reserves of about 346km^3. The estimated ice reserves is higher in central and eastern Nepal than in western Nepal, but the numbers of glaciers are higher in central and western Nepal than eastern Nepal (Fig. 3).

The rapid melting of glaciers fragmented the glaciers with the result of increase in number of glaciers and decrease in glacier area. The overall glacier area of Nepal is reduced from 3.6% to 2.9% of total land of Nepal from 1970 to 2008 (Bajracharya et al., 2010). The largest glacier in the ICIMOD inventory of 2001 was Ktr_gr 193 in Kanchenjunga of Tamor sub-basin, which had a total glacier area of 94km^2 but due to the shrinkage of glacier it has broke down in to two glaciers and the larger part is having the area of around 77km^2, that means the Ktr_gr 193 is no longer the largest glacier in Nepal. The new glacier data shows that the Ngojumba Glacier of Dudh Koshi sub-basin is the largest glacier in Nepal. However, the area of Ngojumba Glacier is also reduced from 82.6km^2 to 80.7 km^2.

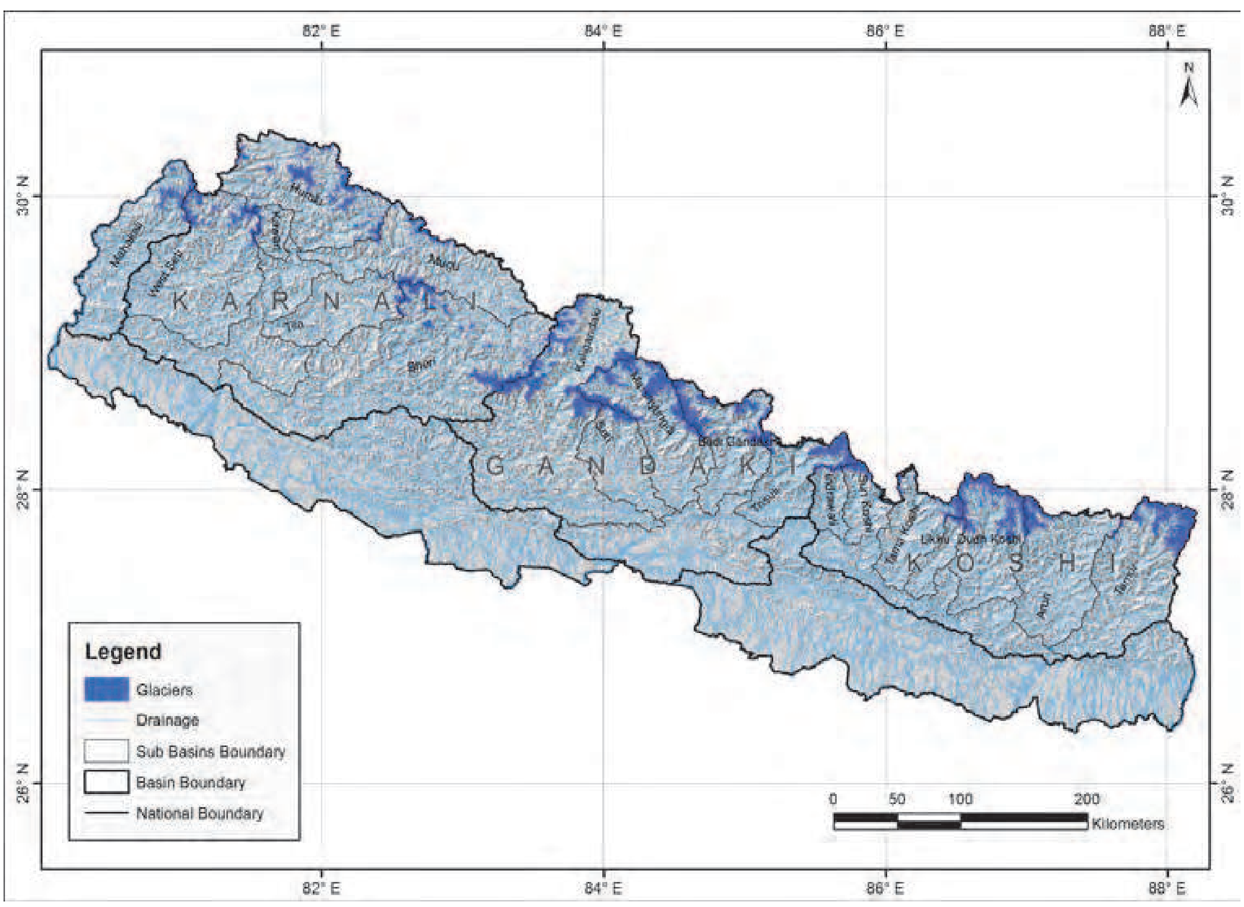


Fig. 3. Glaciers of Nepal

4.1 Change in glacier number, area and estimated ice reserves

The glacier study in 2001 revealed that some 3,252 glaciers covering a total area of 5,323km^2 and including 481km^3 of estimated ice reserves occur in the Nepal Himalaya (Table 1). This was the first information on glaciers of Nepal, which served the important baseline information on glaciers. As the time and source materials were different, the glacier information was heterogeneous and is not matching in the present context due to rapid melting of glaciers as an impact of global warming. The present glacier inventory is based on the single source of Landsat satellite images of 2008 and 2009. The overall glaciers mapped in Nepal are 3808 in number and 4212 km^2 of glacier area with 346km^3 estimated ice reserves.

SN	Sub-basins	Basins	Glacier Inventory 2001			Glacier Inventory 2010		
			Data source: Topomap of 1963 to 1982 and Images of 1999			Data source: Landsat images of 2008/2009		
			No	Area (km^2)	Ice reserve (km^3)	No	Area (km^2)	Ice reserve (km^3)
1	Tamor	Koshi	261	474.15	56.64	261	407.33	45.66
2	Arun		91	216.07	23.47	108	163.81	16.70
3	Dudh		278	482.20	51.01	287	415.10	41.62
4	Tama		80	109.69	10.37	85	93.75	9.03
5	Sun Koshi		23	74.56	7.19	39	57.66	4.81
6	Indrawati		18	22.98	1.44	37	17.91	0.79
7	Likhu		28	30.19	1.94	26	24.30	1.53
8	Trishuli	Gandaki	74	246.65	27.47	163	2 31.66	22.82
9	Budhi		180	442.14	40.40	242	387.40	33.67
10	Marsyangdi		311	614.31	54.99	385	545.38	44.01
11	Seti		61	164.48	16.88	45	72.10	8.35
12	Kali		399	562.67	51.65	502	562.93	43.06
13	Bheri	Karnali	452	583.40	47.77	400	397.33	27.91
14	Mugu		254	220.39	12.52	205	127.78	6.40
15	Tila		58	54.69	3.75	66	39.21	2.05
16	Kawari		39	53.33	3.29	48	33.37	1.78
17	Humla		424	534.53	36.006	474	361.71	20.90
18	West Seti		134	294.13	24.48	268	160.85	8.47
19	Mahakali		87	143.34	10.06	167	112.23	7.13
	Nepal		**3252**	**5323.9**	**481.32**	**3808**	**4212.03**	**346.7**

Table 1. Summary of change in glaciers in 2001 and 2010 Inventory

The inventory of 2010 shows that the number of glaciers in Nepal has increased by about 17% compared to 2001 inventory (Fig. 4). The number of glaciers increased largely due to actual shrinking and fragmentation of the glaciers as an impact of global warming, although the overall glacier area and ice reserve has been decreased by 21% and 28% respectively (Fig. 5 and 6). The glacier area of Nepal is decreasing 30km^2 per year since 1970s. If this trend continues, the glaciers of Nepal will disappear in 140 Years or by 2150AD. As mentioned previously, it cannot be excluded that some of the apparent change between surveys is an artifact of the differing data bases, methodologies, and analysts. Further work is needed to sort through this completely and arrive at final conclusions about actual changes in the glacier numbers, areas, and volumes.

4.2 Change in hypsography

Glacier Area - Altitude of 100m bin is calculated based on the SRTM DEM of 90m resolution in both glacier inventories. During the conversion of glacier polygon from raster to vector, there was a loss of 2% of glacier area which is rectified in the final glacier database.

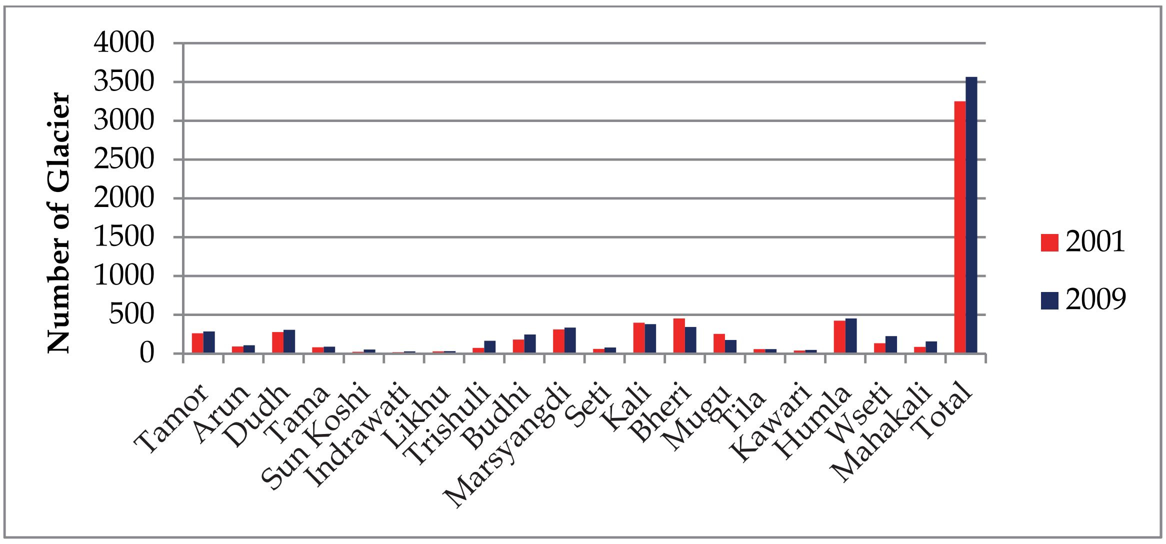


Fig. 4. Comparison of number of glaciers mapped in 2001 and 2010 inventories of Nepal.

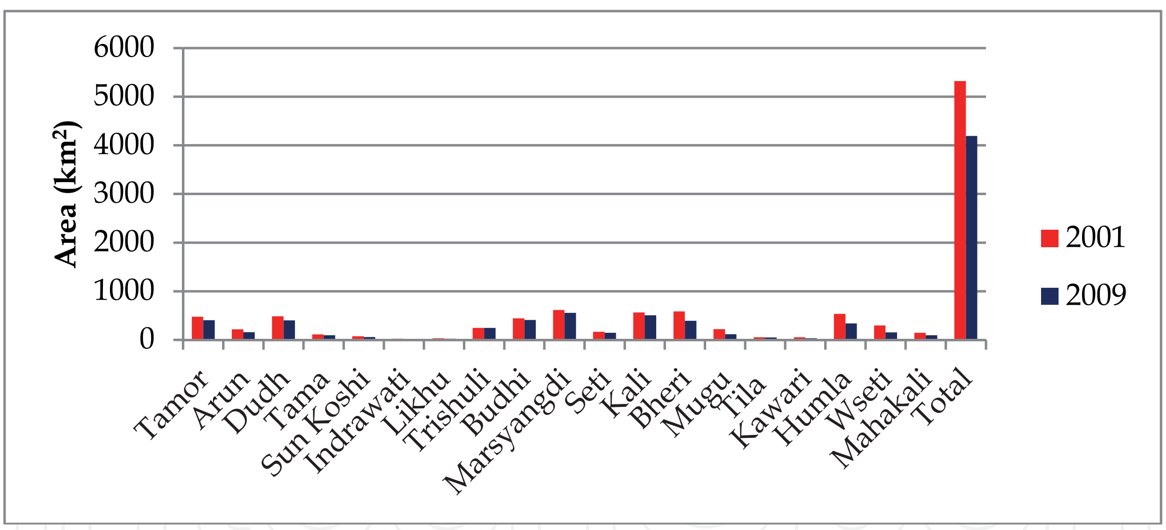


Fig. 5. Comparison of glacierized area mapped in 2001 and 2010 inventories of Nepal.

4.2.1 Glacier hypsography of 2001 inventory

The glaciers were mapped from the elevation 2425 to 8485m asl in Nepal (Fig. 7a). The lowest and highest elevations of glaciers are found from the Gandaki basin and Koshi basin respectively. The lowest elevations of glaciers were mapped from 3536m asl, 3637 and 3940m asl in Karnali, Mahakali and Koshi basins respectively (Fig. 7). The glaciers are densely populated at the elevations of 5000m asl to 6000m asl with the total glacier area of about 3700km^2. The elevations from 5200 to 5500m asl contain about 400km^2 in each 100m bin whereas the elevations below 4500 m asl and above 6300m asl contain less than 100km^2 in each 100m bin.

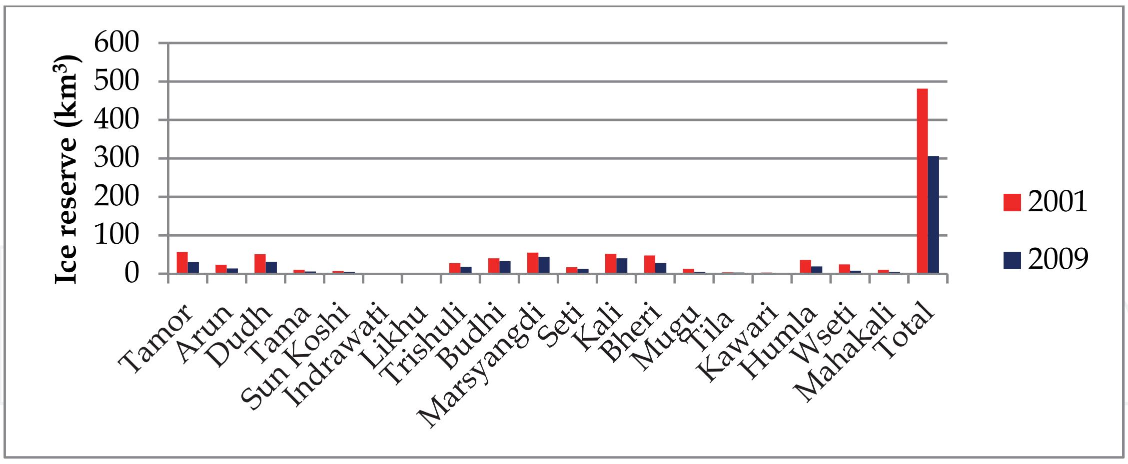


Fig. 6. Comparison of estimated ice reserves in 2001 and 2010 inventories of Nepal

4.2.2 Glacier hypsography of 2010 inventory

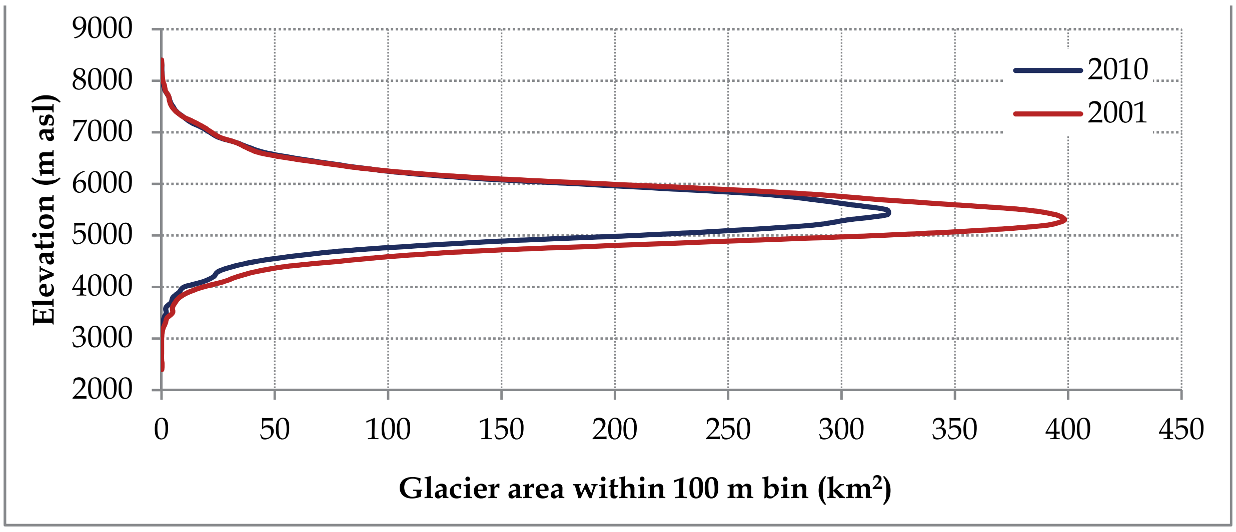
The glacier polygons were delineated from the elevations ranging from above 3200m asl to 8485m asl with lowest in Gandaki basin and highest in Koshi basin as in 2001 inventory. A comparison of the glacier area-altitude distribution for Nepal shows a maximum glacierized area is 320km² at 5500 to 5600 elevation, however more than 100km² are found from 4800 to 6300m asl in each 100m bin (Fig. 7). The highest glacier area in Koshi basin is 100km² at elevation 5400-5500m asl, 140km² at 5800-5900m asl for Gandak basin, 110km² at 5300-5400m asl for Karnali basin and about 10km² at 5000-5100m asl for Mahakali basin.

4.2.3 Change in glacier hypsography

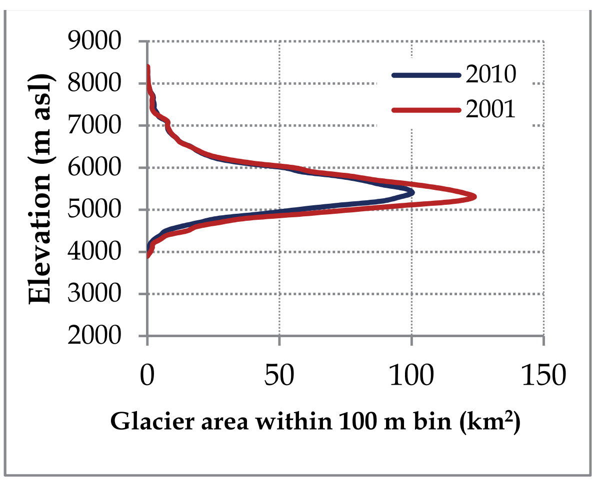
By comparing the glaciers hypsographs of 2001 and 2010 glacier inventory stick out the disappearance of glaciers from the elevations below 3200m asl. It is also noticed that the glacier area has been decreased only from below the elevation 5800m asl of Nepal (Fig. 7).
There are no changes in glacier area of Nepal above 5800m asl (Fig. 7a). However, the threshold value of unchanged glacier area is 5700m asl for Koshi basin, 5900m asl for Gandaki basin and 5600m asl for Karnali basin (Fig. 7). In contrary to this the glacier area is increased in Mahakali River basin above 5500m asl but the glacier area has shrunk comparatively very high at the elevations of 5300 to 4000m asl. The glacier area is reduced maximum from the elevation 5000 to 5500m asl in Nepal. The glacier area loss percentage is higher in Koshi and Mahakali basins, moderate in Karnali basin and low in Gandaki basin. However the cumulative glacier area loss shows constant in Koshi, Gandaki, Karnali and throughout Nepal except in Mahakali basin (Fig. 8). The glacier retreat rate is higher in Karnali and Mahakali River basins below 5000m asl compared to other basins of Nepal. The low retreat rate in lower elevations in other basins might be due to the presence of debris cover.

4.3 Decadal glacier area change in Langtang valley of Trishuli basin

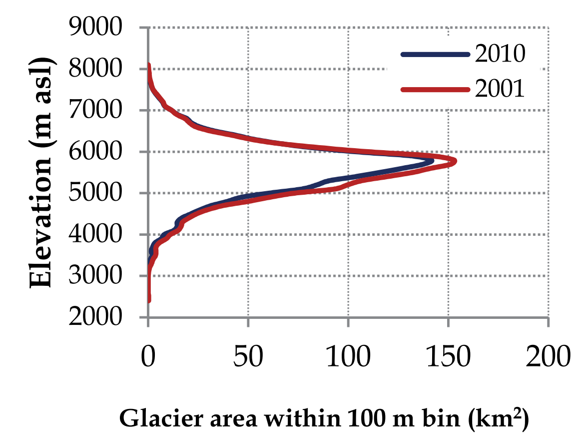
Based on the developed methodology, an attempt of a decadal change of glaciers in Langtang sub-basin of Trishuli River was made. For this, base maps of glacier polygons were established from the recent satellite image. The glacier polygons derived from Landsat 7 ETM+ image of 2009 were used as a base map of glacier to that year and by overlaying the glacier polygons of 2009 on the older satellite images of 1977, 1988 and 2000, the polygons were edited and modified to that years separately. In this way the glaciers of 1977, 1988, 2000 and 2009 were generated and compared for the change graphically and spatially.



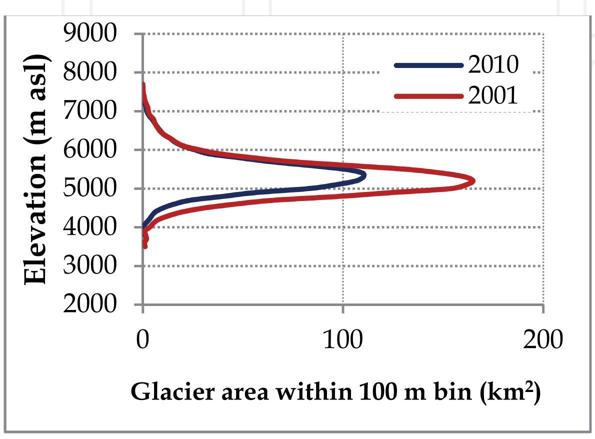
a. Nepal



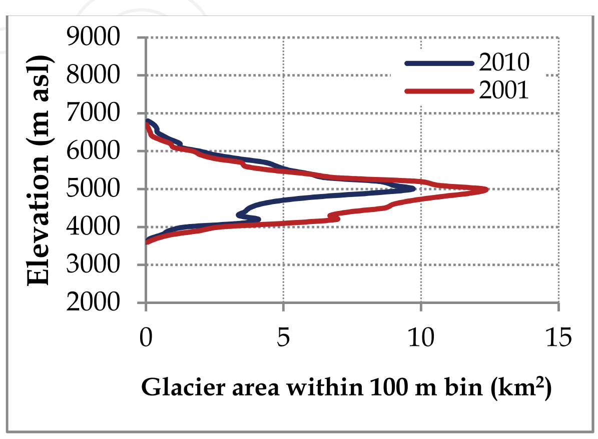
b. Koshi



c. Gandaki

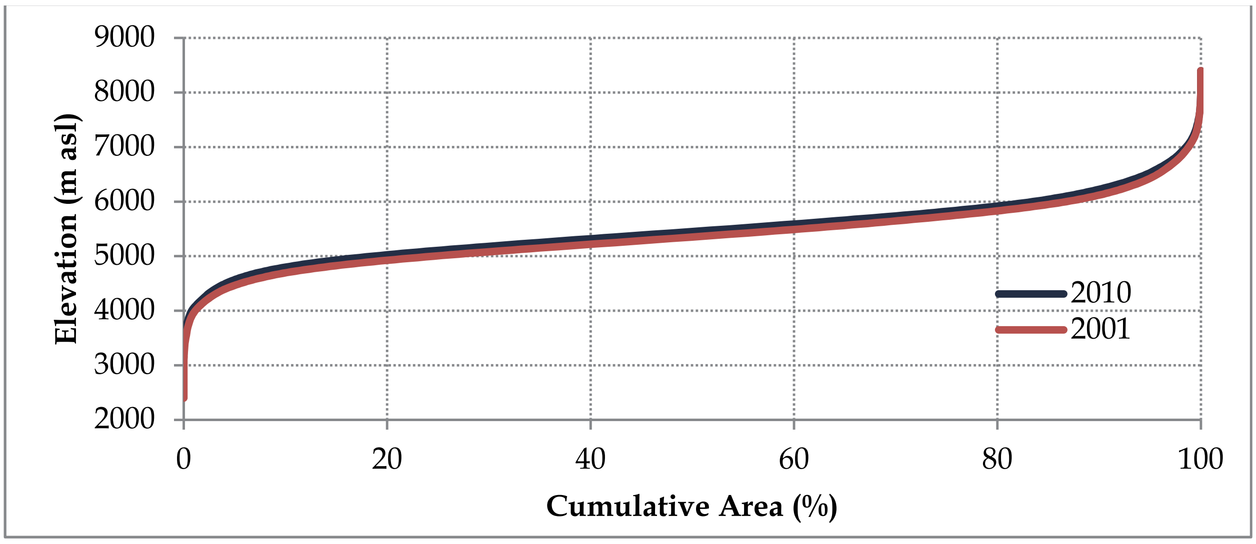


d. Karnali

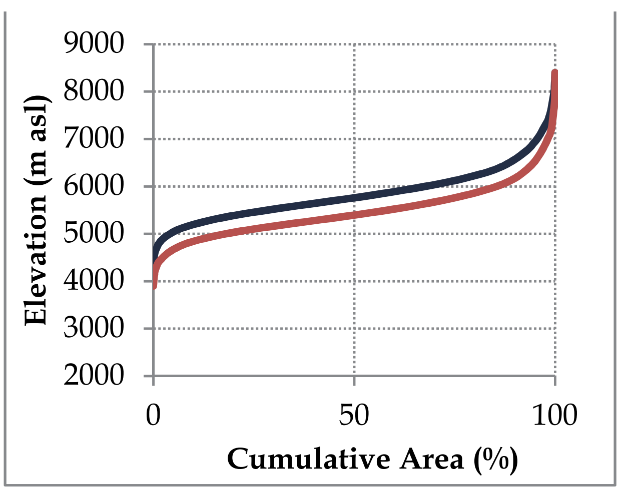


e. Mahakali

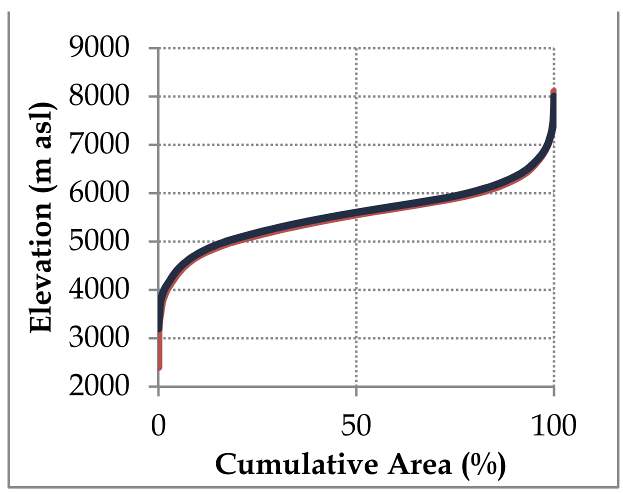
Fig. 7. Hypsograph of glaciers of 2001 and 2010 inventory.



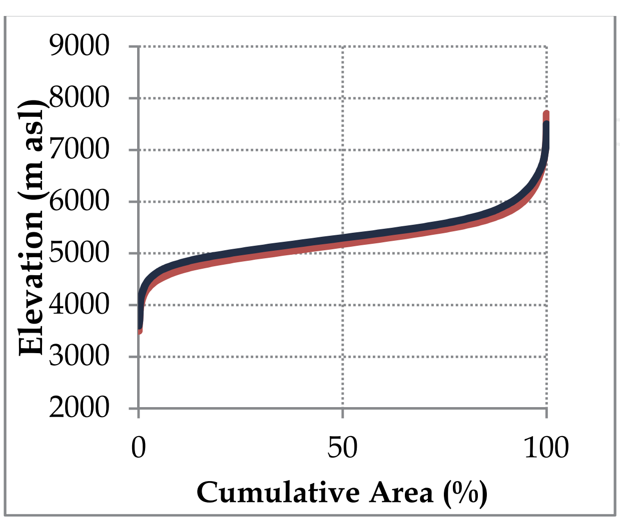
a. Nepal



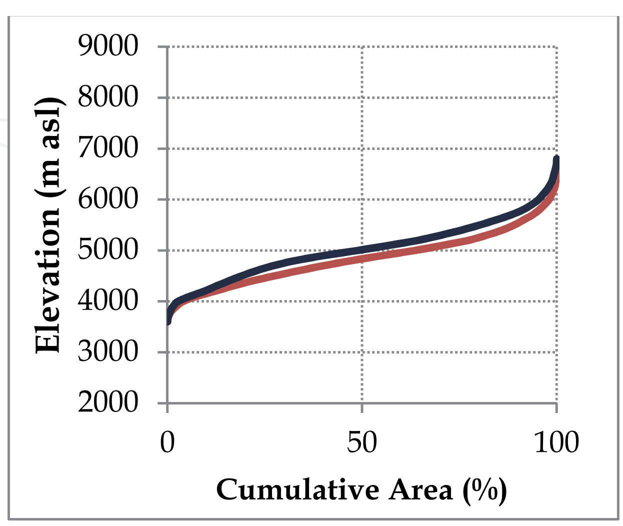
b. Koshi



c. Gandaki



d. Karnali



e. Mahakali

Fig. 8. Comparative cumulative area - altitude of glaciers in 2001 and 2010 inventory.

The Langtang sub-basin is a small northeast-southwest elongated basin, tributary of Trishuli River north of Kathmandu and bordered with China to the north. The basin encompasses an area of 554km². The basin contains 192km² of glacier area in 1977 and changes to 171km² in 1988, 152km² in 2000 and 142km² in 2009. In 32 years from 1977 to 2009 the glacier area is reduced by 26%. The decrease in glacier area is recorded below the elevation 5800m asl. Due to shrinkage of glaciers the snout elevations of Lirung and Kimjung Glaciers shifted vertically 100m upward and the snout of Yala Glacier by 100 to 150m (Fig. 9).

5. Discussion

The data sources and methods of the two inventories differ, until further study is undertaken of the older survey, conclusions regarding temporal changes are considered tentative. Questions remain about whether the increase in numbers of glaciers is due mainly to (1) actual fragmentation of glaciers, (2) reduced snow cover in the more recent survey, or (3) a more detailed mapping in the more recent survey. With either the second or third explanations, it would be likely that the first survey overestimated the glacier area and underestimated the total number of glaciers, whereas under the first explanation the changes documented between the two surveys are real. A great deal of evidence has accumulated to show that the long valley glaciers of Nepal have, for the most part, retreated drastically in the past few decades, and since these glaciers contribute so strongly to the total areas occupied by glaciers, the decreased glacier area between the two periods of the two inventories is very likely to be correct. However, a focused scrutiny of the earlier survey, and a cross comparison of the two surveys in sample areas, is needed to gain full confidence in the documented changes indicated here, especially with regard to the number of glaciers. In any case, the change in number of glaciers occurs mainly at the smaller glacier sizes, which are much less significant than the big glaciers with respect to their contributions to total glacier area, estimated ice reserves, and river flow.

Consideration below of just one example, that of what was once Nepal's largest glacier, Ktr_gr 193, which fragmented into two glaciers subsequent to the first survey, shows that this phenomenon of fragmentation is not restricted to small glaciers. Nevertheless, a detailed quantitative comparison of the two inventories is needed and recommended for the near future. A good approach could be a blind re-inventory, using the same methodology and same analysts of a small sample of glaciers using the old data used in the first inventory, and then comparison with the first inventory results.

The elevations of the glaciers in Nepal range from 8485 to 3273m asl. The glacier snout elevation ranges from basin to basin, the lowest elevation of glacier extension is about 3300m asl in Gandaki basin in central Nepal, about 3600m asl in Karnali basin of western Nepal and about 4000m asl in Koshi basin of eastern Nepal.

Space based monitoring of glaciers is a valuable aid to climate change scientist, policy makers and civil engineers assigned to water resources and climate change researchers, though these methods have their limitations as well (Fujita et al. 2009; Kargel et al. 2011). Accurate knowledge of overall glaciers will enhance each nation's abilities to deal with the water resources. A digital GIS repository of relevant data then can inform policy makers to make sensible decisions on responsible development and land management.

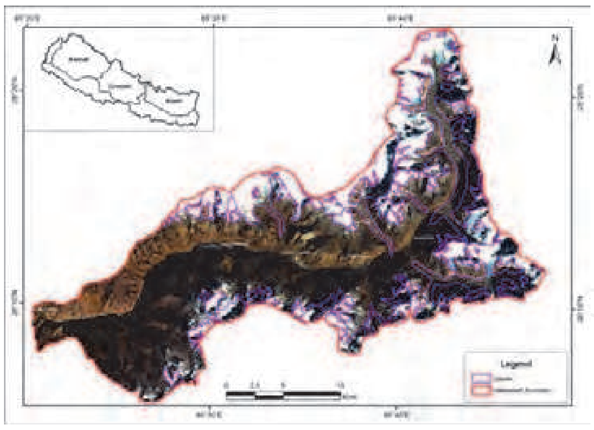


Fig. 9a. Glaciers in 1977

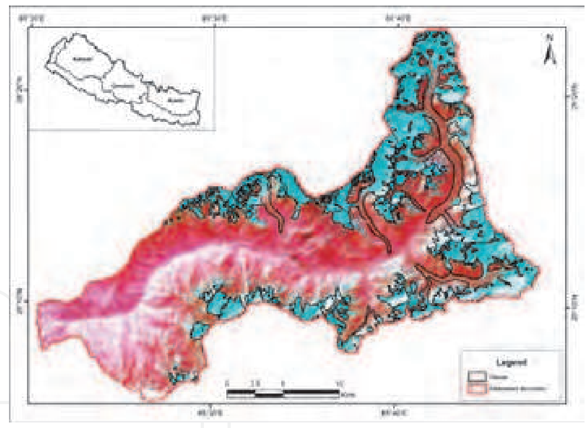


Fig. 9b. Glaciers in 1988

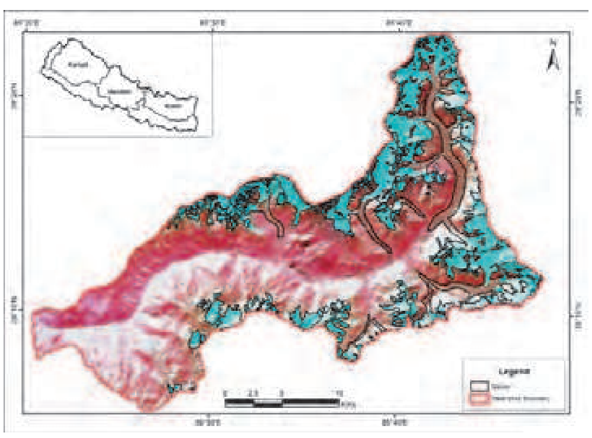


Fig. 9c. Glaciers in 2000

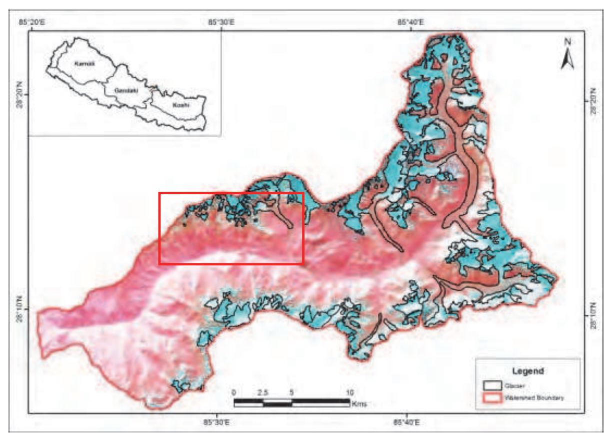


Fig. 9d. Glaciers in 2009

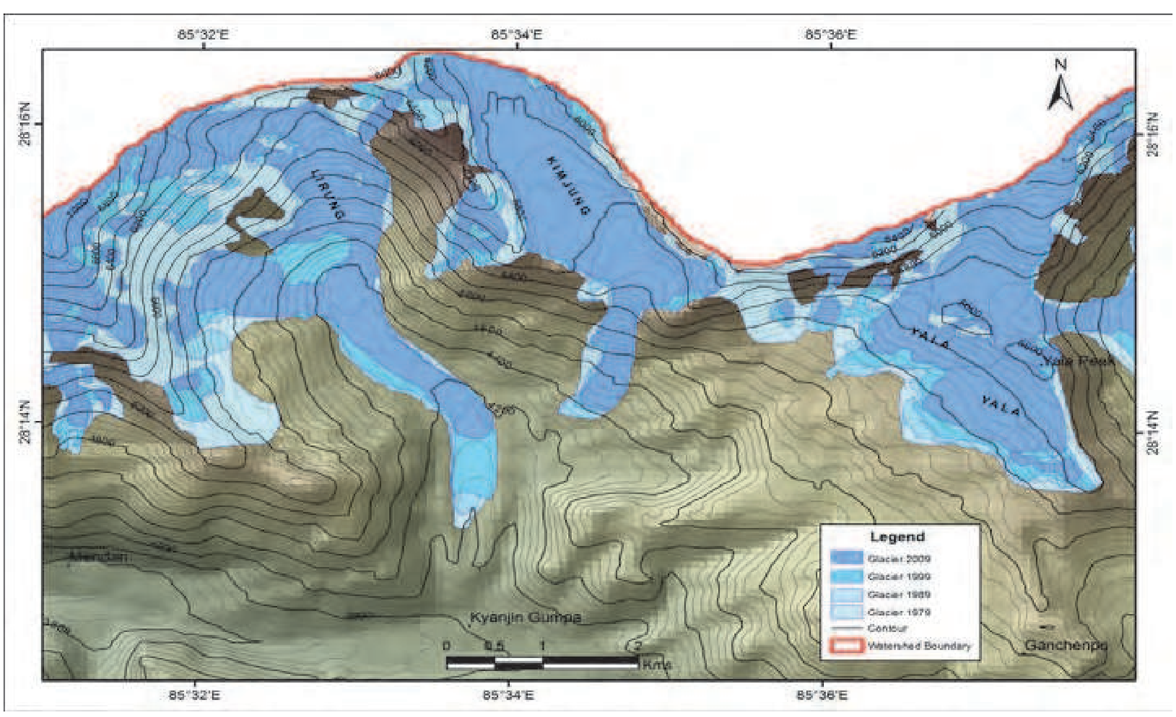


Fig. 9. Glacier area change in Lirung, Kimjung and Yala Glaciers of Langtang Valley.

6. Conclusions

The Himalayan region is one of the most dynamic, fragile and complex mountain ranges in the world due to tectonic activity and a rich diversity of climates, hydrology and ecology. The high Himalayan region is the fresh water tower of south Asia. The melt of snow and ice from these towers feeding the ten largest river systems in Asia, on which over 1.3 billion peoples are dependent. Glaciers and snowmelt runoff from the mountains is of course just a part of the water supplies of these rivers. However, in a chronically water-short and in places an over-populated region, these alpine sources of water are very important, especially for populations in the proximal river valleys. In the context of global warming the glaciers are melting rapidly causing the shrinking, subsidence and retreating of glaciers with the result of expansion and formation of glacial lakes to the stage of potential glacial lake outburst floods. The glacier retreat phenomena has been taking place rapidly in recent decades, with the common and widespread fear of too much water (GLOFs) and too little water (glacier retreat). If it continues for long period definitely there will be negative balance of ice with the deficiency of fresh water resources and increase in the frequency of GLOF disasters in near future. In some places, increased melting of glaciers might provide a temporary surge in water supplies lasting some decades, and in other places, retreat and disappearance of glaciers can cause a disappearance of certain types of mountain hazards and disasters. In general, however, rapidly changing glaciers are both caused by instabilities in climate and further cause new instabilities in the natural system. The instabilities can impact people severely, especially those residing within or near the mountains. For the quick delivery of glacier data a semi-automatic method was developed using the advanced remote sensing and geographic information systems tools and techniques. The primary glacier data upon analysis was performed consist of the Landsat satellite images of 2008 and 2009. This study will help to understand the glaciers dynamics in the Himalaya. Some imperative findings of this study are listed below:

- Due to shrinkage of glaciers, the number of glaciers has increased due to fragmentation of glaciers. There has been about a 17% increase in the numbers of glaciers compared to the inventory of 2001.
- The area and estimated ice reserves of glacier have declined 21% and 28%, respectively, compared to the inventory of 2001.
- The glaciers below 3200m asl has been disappeared from Gandaki basin.
- The glacier area is shrinking and retreating only below the 5800m asl in Nepal.
- The glaciers are advancing in Mahakali basin above 5800m asl but the retreat rate is higher in Mahakali and Karnali below the elevation 5000m asl.
- The glacier retreat rate is high at the elevations 5000 to 5500m asl. The low retreat rate below 5000m asl may be due to the presence of debris cover glaciers.

7. Acknowledgement

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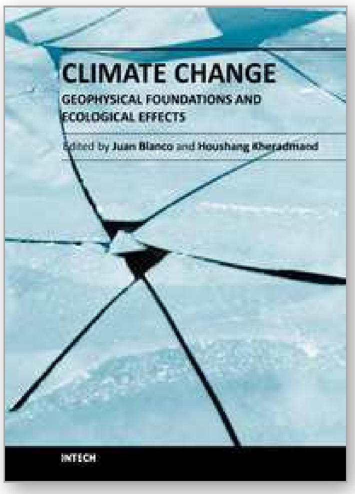

Climate Change - Geophysical Foundations and Ecological Effects
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This book offers an interdisciplinary view of the biophysical issues related to climate change. Climate change is a phenomenon by which the long-term averages of weather events (i.e. temperature, precipitation, wind speed, etc.) that define the climate of a region are not constant but change over time. There have been a series of past periods of climatic change, registered in historical or paleoecological records. In the first section of this book, a series of state-of-the-art research projects explore the biophysical causes for climate change and the techniques currently being used and developed for its detection in several regions of the world. The second section of the book explores the effects that have been reported already on the flora and fauna in different ecosystems around the globe. Among them, the ecosystems and landscapes in arctic and alpine regions are expected to be among the most affected by the change in climate, as they will suffer the more intense changes. The final section of this book explores in detail those issues.

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