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Change in Glacial Environment of Everest Region, Nepal

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ABSTRACT

The climate variability and global climatic change has brought significant impact on the glacial environment of Everest region. The rapid melting of glaciers had result of reduction of glacier mass with the increase in size of moraine dammed glacial lakes. The merging and expansion of supraglacial lakes at the snout of the valley glacier had formed moraine dammed lakes. Most of these lakes had formed only on the second half of twentieth century as an impact of global warming. The expansion of these lakes leading to the stage of glacial lake outburst floods (GLOF). The Himalaya had experienced at least one catastrophic GLOF event in three to ten years period.

The area of the glaciers in the Everest region is first mapped by ICIMOD in 2001 using the topographic maps published by Survey of India from 1959 to 1982 based on the aerial photographs of 1957 to 1959 and hence referred the data from 1960's. The total area covered by the glaciers in the Everest region was about 482 sq km in 1960's and the glacier area mapped of the region from the satellite was only 473 sq km in 2000. The significant glacier area reduced was noticed from the small glaciers and valley glacier snouts extending down to the low elevation. However the reduction of total area is small but the length of the valley glaciers are retreating at a rate of 10 to 60m/yr in average. The shrinking of glacier mass split the glacier body with the increase in number and decreases in area. The numbering of glaciers was based on the World Glacier Inventory (WGI) methodology. In general, the glaciers are shrinking and retreating faster in the recent decade with the proliferation of moraine dammed lakes, which might pose GLOF danger in future and some of it had already catastrophic outburst event. Hence the lakes which are mapped in the region and identified as potentially dangerous lakes poses different scenario in the present days.

INTRODUCTION

The Everest region in the Dudh Koshi basin of eastern Nepal is one of the important and largest basins of Nepal in terms of glaciers and glacial lakes, perhaps the most densely glaciated region of eastern Nepal (Bajracharya et al. 2004). The glaciers in the region are extending down to the latitude of 27^{o} 38’ 05” and lowest elevation 4206 masl, however the snout of most of the glaciers are at around 5000masl. The climate variability and global climatic change has brought significant impact on the high mountainous glacial environment. The glaciers are melting faster than the accumulation resulting negative balance and growing moraine dammed lakes leading to the stage of glacial lake outburst floods (GLOF). Most of these lakes which are accounted from the elevation above 3500 masl had formed only on the second half of twentieth century as an impact of global warming. As a result some of the lakes had breached out to the stable condition and others are growing to the stage of danger condition. Understanding of these glacial environments is an imperative aspect in planning of water resources as well as GLOF disaster management in the region.

GLACIAL ENVIRONMENT

The glaciers and glacial lakes mapped by ICIMOD in 2001 were mainly based on the topographic maps published in 1959 to 1982 by Survey General of India. The potentially dangerous glacial lakes were identified on the basis of different parameter using the temporal satellite images from 1975 to 2000. In the context of global warming and fast retreating glaciers, the moraine dammed lakes are growing fast to the stage of potentially dangerous and some of it had GLOF and remain to the stable condition.

Glaciers

The glaciers mapped in the basin are 278 in number with the total area of 482 sq km and ice reserve of 51 cubic km (Mool et al 2001). The glaciers in the region are distributed in the high mountains. However, the large glaciers extending down to the valley are 40 in number covering more than 70% in area. The Ngojumba, Khumbu, Bhote Koshi and Hongu are the major glaciers in Dudh Koshi basin with the area of 82.61, 45.39, 35.63 and 22.91 sq km respectively. The change mapping of glaciers were carried out from the satellite images of 1976 (Landsat MSS), 1992 (Landsat TM), 2001 (Landsat etm+) and 2007 (ALOS). Significant change can be seen only in the snout of the valley glaciers (Figure 1). Due to certain limitations of the remote sensing (such as shadows, poor resolution, etc.), only 24 valley glaciers have been studied to identify their retreat rate. The average minimum glacier retreat rate was 10m/yr; this was observed on the Langdak, W. Lhotse, Lhotse, and Setta glaciers. The fastest retreating glaciers were the Imja and Lumding glaciers with an average rate of 74m per year from 2000 to 2007. Other fast-retreating glaciers are West Chamiang and Ombigaichain (Table 1). Most of the Valley glaciers are shrinking and retreating faster in the recent decade.

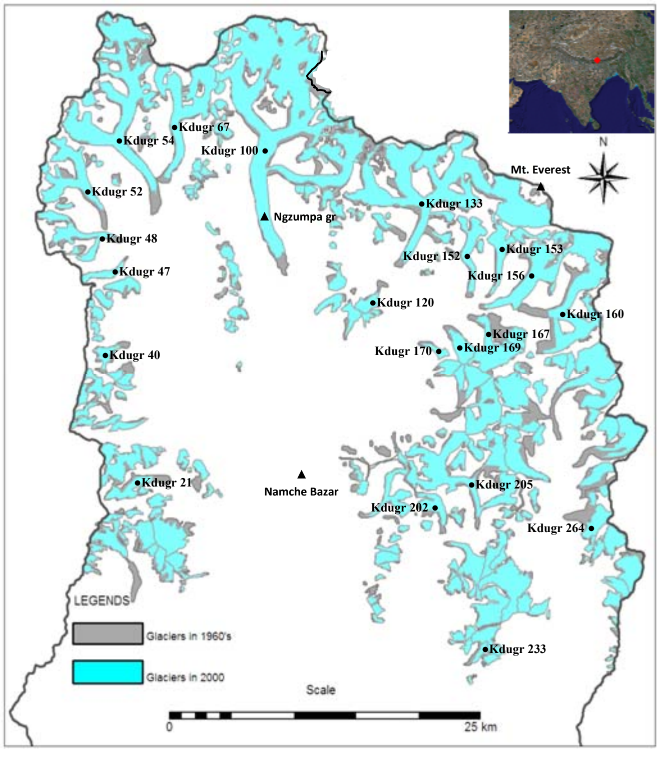
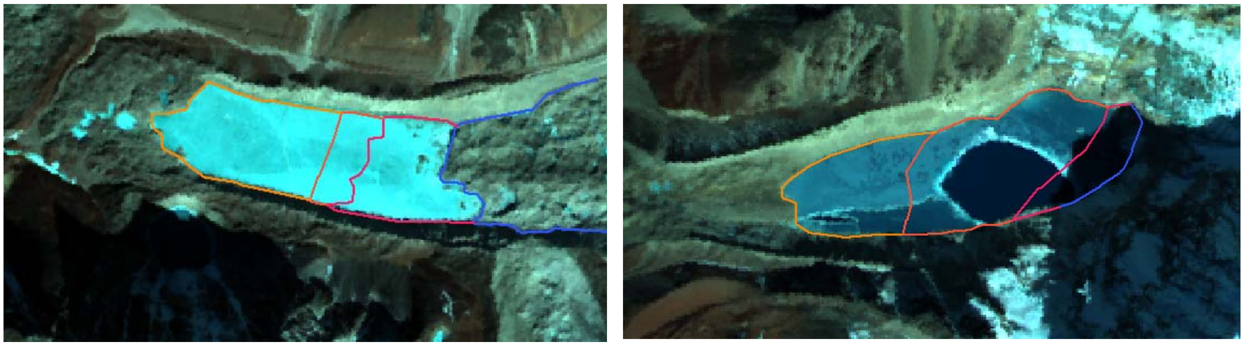


Figure 1: Change of glaciers in Dudh Koshi basin from 1960’s to 2000

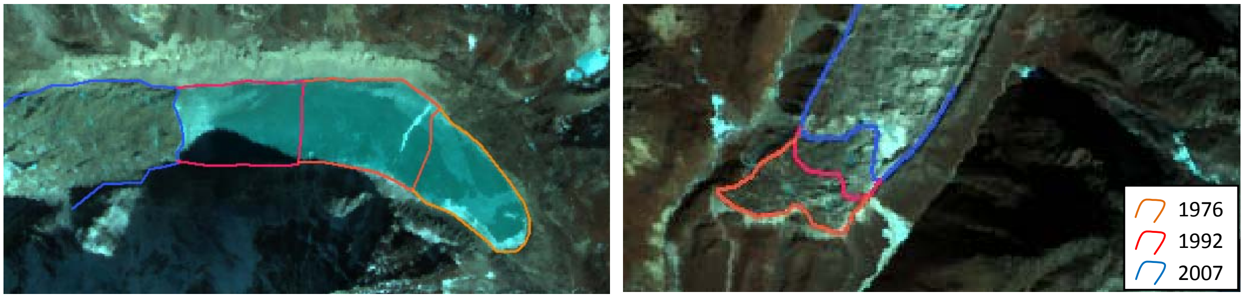
Table 1: Retreat rate of Valley glaciers in Dudh Koshi basin

S.N.	Glacier ID	Glacier Name	Mean length (m) in year					Avg. retreat rate (m/year)	
			1960s	1976	1992	2000	2007 Jan	1976–2000	2000-2007
1	Kdugr 21	Lumding	6,015	5,715	4,884	4,700	4,255	42	74
2	Kdugr 40	Langmuche	3,160	2,711	2,711	2,388	2,388	13	0
3	Kdugr 47	Langdak	4,430	4,237	4,237	4,028	3,764	9	44
4	Kdugr 48	Chhule	7,600	7,352	7,352	6,818	6,658	22	27
5	Kdugr 52	Melung	8,870	7,805	7,430	7,430	7,378	16	9
6	Kdugr 54	Bhote Koshi	17,100	16,855	16,785	16,455	NA	17	NA
7	Kdugr 67	Lumsamba	9,500	9,421	9,197	8,955	NA	19	NA
8	Kdugr 100	Ngojumba	22,500	21,975	21,925	21,625	21,543	15	14
9	Kdugr 120	Cholo	2,520	2,339	1,756	1,586	1,293	31	49
10	Kdugr 133	Khumbu	12,040	11,681	11,343	11,198	11,097	20	17
11	Kdugr 152	Nuptse	6,330	6,207	6,022	5,898	5,898	13	0
12	Kdugr 153	W.Lhotse	4,110	3,908	3,838	3,722	3,722	8	0
13	Kdugr 156	Lhotse	8,870	8,733	8,626	8,453	8,335	12	20
14	Kdugr 160	Imja	10,770	9,242	8,988	8,430	7,986	34	74
15	Kdugr 166	Ombigaichain	4,110	3,328	3,117	2,123	2,033	50	15
16	Kdugr 167	Amadablam	5,060	4,951	4,911	4,311	4,311	27	0
17	Kdugr 169	Duwo	2,530	2,446	2,357	2,056	2,056	16	0
18	Kdugr 170	Tsuro	2,215	2,087	2,066	1,811	1,811	12	0
19	Kdugr 186	Kyashar	6,330	Shadow	6,042	5,797	5,662	NA	23
20	Kdugr 202	Sabai (Sha)	4,110	3,511	3,511	3,511	3,456	0	9
21	Kdugr 205	Inkhu	10,770	10,610	10,347	9,786	9,721	34	11
22	Kdugr 221	Kdugr 221	3,160	Shadow	3,050	2,683	2,683	NA	0
23	Kdugr 233	Kdugr 233	1,900	1,589	1,487	1,259	1,259	14	0
24	Kdugr 264	W.Chamiang	3,800	2,573	2,108	1,558	1,433	42	21



a. Imja Glacier and Tsho

b. Glacier Kdu_gr 262 (Kdu_gl 464) in Hungu Valley



c. Lumding Glacier and Tsho

d. Khumbu Glacier

Figure 2: Some examples of glacier retreat and lake expansion from the Dudh Koshi basin

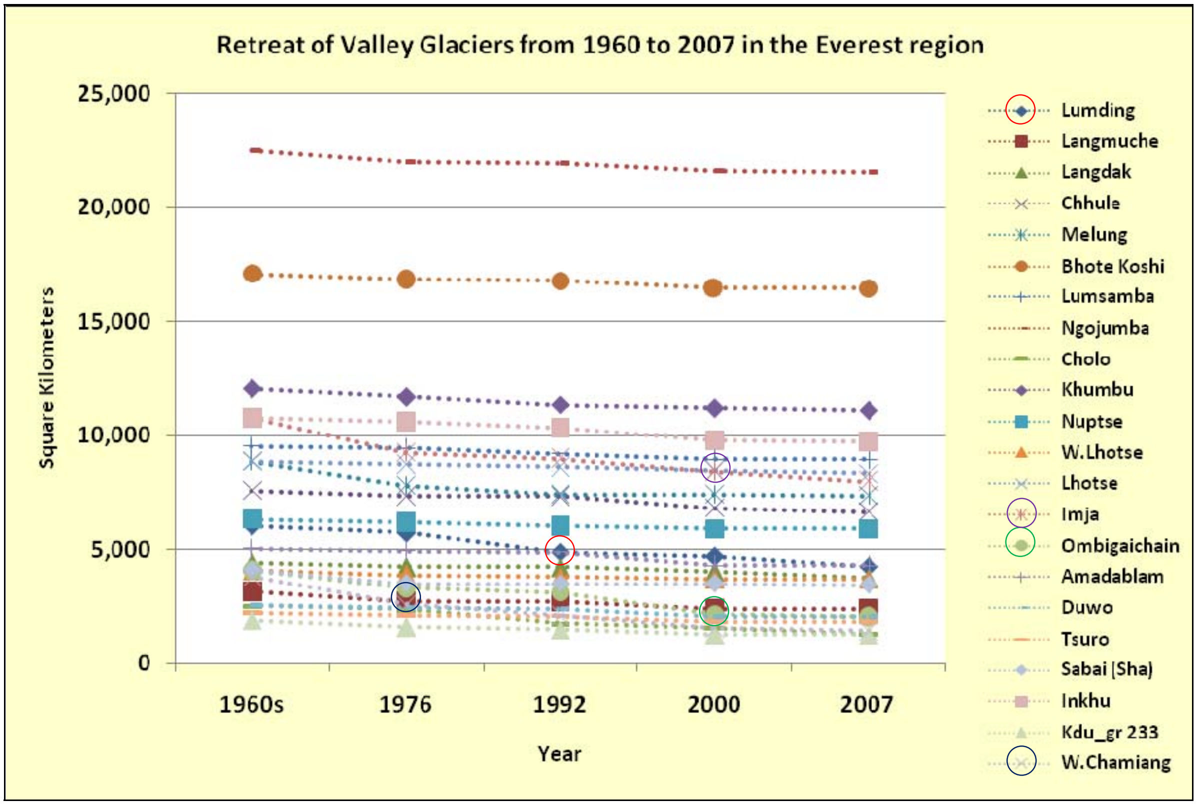


Figure 3: Retreat trend of the valley glaciers in the Everest region from 1960 to 2007

Figure 4: Change in Imja glacier from 1955 to 2007 (Source: ICIMOD, Alton C Byers, 2007 and Fritz Muller, 1955)

Glacial lakes

The glacial lakes larger than 0.003 sq km situated above an altitude of 3500 masl are 473 in number in the Dudh Koshi basin. The important lakes in the basin are Lumding Tsho, Dig Tsho, Imja Tsho, Tam Pokhari, Dudh Pokhari, Hungu, Chamiang and others. Bajracharya and Mool, 2005 mapped only 296 lakes from the landsat satellite image of 2001. They found the disappeared lakes were mostly the supraglacial and erosion lakes. Most of the supraglacial lakes are either small in size to map or disappeared. Some of it had transformed to moraine-dammed lakes. The number of glacial lakes had decreased by approximately 37 per cent, while 21 per cent of the lakes associated with the glaciers had increased in size. The increased percentage in surface area is due to the proliferation of moraine dammed lakes. In addition, 34 major glacial lakes are growing and 24 new major lakes have appeared. The newly formed lakes are 15 Moraine-dammed lakes, 5 Supraglacial lakes, 2 Valley lakes and 2 Erosion lakes (Table 2). The areas of the major glacial lakes range from 0.021 to 0.848 sq km at altitudes between 4,349 and 5,636 masl.

The fast and continuous retreat of glaciers and growing of glacial lakes highlights the importance of monitoring of glaciers and glacial lakes for the sound management of water resources. However, the study of this phenomenon is a challenge with the limits imposed by the higher altitude, the rarefied atmosphere, the remoteness of many of the locations and the short mapping season.

Table 2: Summary of activity of glacial lakes in the Dudh Koshi sub-basin (1960 –2000)

1. Disappeared (or less than 50×50 sq m) lakes	**245**
Supraglacial lakes	199
Erosion lakes	34
Valley lakes	3
Moraine-dammed lakes	7
Cirque	2
2. Converted lakes (from supraglacial to Moraine-dammed Lakes)	**11**
3. New lakes	**24**
Supraglacial lakes	5
Erosion lakes	2
Valley lakes	2
End moraine-dammed lakes	15
4. Growing lakes	**34**
Supraglacial lakes	10
Valley lakes	2
Moraine-dammed lakes	17
Blocked lakes	2
Erosion lakes	3

Based on the satellite images of 2000 and 2007, the main glacial lakes of the basin are monitored by automatic boundaries delineation of the lake using remote sensing techniques. Depending upon the projection of the satellite images the reliability of the data is more than 90%. The growth rate of the lakes from 2000 to 2007 indicates mostly negative value due to the seasonal variation of the lake. The image used for the analysis was from January 2007 during that period most of the lakes at high altitude are frozen and least extended in the year, however some of the lakes like Kdu_gl 71 and Kdu_gl 543 had grown significantly.

Table 3: Activity of glacial lakes in association with glaciers in the Dudh Koshi sub-basin

S.N.	Lake		Type	Area (sq m) in			Distance to glacier (m)	Growth rate	
	Number	Latitude, longitude		1960s	2000	2007		60 - 00 (%)	00 – 07 (%)
1.	Kdu_gl 40	27°47'44"N, 86°37'14"E	M dammed	18,914	23,289	22,319	270	23	-4
2.	Kdu_gl 41	27°47'41"N, 86°37'36"E	M dammed	26,289	74,197	92,951	785	182	25
3.	Kdu_gl 43	27°47'09"N, 86°38'06"E	M dammed	13,662	25,888	26,721	70	89	3
4.	Kdu_gl 47	27°49'14"N, 86°35'38"E	Blocked	12,866	35,593	Shadow	45	177	NA
5.	Kdu_gl 52	27°49'38"N, 86°34'38"E	M dammed	2,096	30,921	33,131	785	1375	7
6.	Kdu_gl 69	27°57'06"N, 86°34'44"E	Supraglacial	3,316	23,322	19,168	0	603	-18
7.	Kdu_gl 71	27°56'39"N, 86°33'15"E	Supraglacial	4,404	21,194	54,101	300	381	155
8.	Kdu_gl 160	27°57'38"N, 86°39'58"E	Erosion	15,439	27,473	24,488	670	78	-11
9.	Kdu_gl 229	27°56'03"N, 86°44'42"E	Erosion	17,933	20,184	22,210	515	13	10
10.	Kdu_gl 255	27°57'23"N, 86°48'37"E	Supraglacial	10,425	48,496	12,284	0	365	-75
11.	Kdu_gl 286	27°59'36"N, 86°50'30"E	Supraglacial	6,765	22,191	13,659	0	228	-38
12.	Kdu_gl 287	27°59'51"N, 86°50'20"E	Supraglacial	48,811	121,762	121,999	0	149	0
13.	Kdu_gl 300	27°57'38"N, 86°50'06"E	Block/valley	16,606	23,474	22,110	95	41	-6
14.	Kdu_gl 342	27°55'08"N, 86°54'50"E	Supraglacial	6,977	41,503	9,144	0	495	-78
15.	Kdu_gl 384	27°53'09"N, 86°50'50"E	M dammed	14,431	29,750	23,711	245	106	-20
16.	Kdu_gl 446	27°49'58"N, 86°55'18"E	M dammed	207,314	349,263	357,903	0	68	2
17.	Kdu_gl 472	27°42'40"N, 86°58'48"E	M dammed	6,526	46,215	49,900	0	608	8
18.	Kdu_gl 483	27°43'39"N, 86°34'22"E	M dammed	New	34,016	32,040	0	NA	-6
19.	Kdu_gl 491	27°46'39"N, 86°38'44"E	M dammed	New	286,119	305,913	245	NA	7
20.	Kdu_gl 495	27°54'32"N, 86°35'00"E	M dammed	New	20,044	23,582	405	NA	18
21.	Kdu_gl 501	27°57'30"N, 86°39'50"E	M dammed	New	60,039	38,937	270	NA	-35
22.	Kdu_gl 502	27°59'20"N, 86°39'06"E	M dammed	New	58,097	55,811	0	NA	-4
23.	Kdu_gl 505	27°56'10"N, 86°42'48"E	Supraglacial	New	48,184	56,412	0	NA	17
24.	Kdu_gl 511	27°59'27"N, 86°41'38"E	Supraglacial	New	27,858	18,444	0	NA	-34
25.	Kdu_gl 513	28°02'30"N, 86°42'31"E	M dammed	New	38,349	32,060	210	NA	-16
26.	Kdu_gl 517	27°48'38"N, 86°50'52"E	M dammed	New	69,238	66,056	0	NA	-5
27.	Kdu_gl 521	27°53'13"N, 86°54'01"E	M dammed	New	65,368	59,541	0	NA	-9
28.	Kdu_gl 522	27°53'00"N, 86°53'43"E	M dammed	New	22,274	13,317	135	NA	-40
29.	Kdu_gl 524	27°42'49"N, 86°55'12"E	M dammed	New	67,607	66,011	310	NA	-2
30.	Kdu_gl 526	27°43'28"N, 86°54'13"E	M dammed	New	31,381	34,001	170	NA	8
31.	Kdu_gl 528	27°49'26"N, 86°55'54"E	M dammed	New	46,225	36,571	880	NA	-21
32.	Kdu_gl 536	27°58'08"N, 86°42'05"E	Supraglacial	New	27,084	19,604	0	NA	-28
33.	Kdu_gl 543	27°45'57"N, 86°52'31"E	Supraglacial	New	21,467	44,821	0	NA	109

Due to different satellite image and projection parameter the data is 90 to 95% accuracy.

Potentially dangerous glacial lakes

A fast retreating of glaciers providing the increased run off and growth of glacial lakes and some of the supraglacial lakes are converted to moraine dammed lakes. The rapid growth of these lakes has the tendency of breaching the weak and unstable loose moraine dam with the catastrophic impact in the downstream valleys. Despite from the numerous glaciers and glacial lakes, the basin contains 12 potentially dangerous glacial lakes, the largest number in any sub-basin of Nepal. All those lakes are dammed by loose and unstable moraine. Among the listed potentially dangerous glacial lakes, three lakes: Kdu_gl 422, 442 and 462 had remained more or less same size; Kdu_gl 444 dried up in 2000 and reappeared in the satellite image of 2007; Kdu_gl 399 (Tam Pokhari) and Kdu_gl 55 (Dig Tsho) already had the outburst event in the past (Table 4). The remaining six lakes (Kdu_gl 28, 350, 449, 459, 464 and 466) are growing. The lake Kdu_gl 350 (Imja Tsho) is one of the fastest growing lakes in the Himalaya. Most likely the basin will have another GLOF event in near future.

Table 4: Status of potentially dangerous glacial lakes in Dudh Koshi sub-basin in 2007

Lake ID	Name	Altitude (masl)	Length (m)			Area (sq m)			Remark
			1960s	2000	2007	1960s	2000	2007	
Kdu_gl 28	Lumding Tsho	4,846	625	1,952	2,180	104,944	836,765	940,077	Growing
Kdu_gl 55	Dig Tsho	4,364	605	1,262	1,263	143,250	375,681	403,044	GLOF on 4 Aug 1985 **No danger**
Kdu_gl 350	Imja Tsho	5,023	410	1,822	2,027	48,811	848,742	945,662	Rapidly growing
Kdu_gl 399	Tam Pokhari	4,431	515	925	898	138,846	265,386	255,495	GLOF on 3 Sep 1998
Kdu_gl 422	Dudh Pokhari	4,760	1,120	1,095	1,159	274,297	297,574	316,767	No remarkable change
Kdu_gl 442	Unnamed	5,266	840	1,082	1,075	133,753	194,966	188,559	No remarkable change
Kdu_gl 444	Unnamed	5,056	420	x	235	112,398	x	25,376	Dried/reappeared **No danger**
Kdu_gl 449	Hungu	5,181	875	1,054	1,327	198,905	232,842	267,720	Merged with gl 532
Kdu_gl 459	East Hungu 1	5,379	465	982	1,105	78,761	296,886	222,102	Merged with 460
Kdu_gl 462	East Hungu 2	5,483	640	448	459	211,877	178,317	164,098	Area decreasing
Kdu_gl 464	Unnamed	5,205	1,100	1,918	2,251	349,397	783,553	835,131	Growing in size
Kdu_gl 466	W. Chamiang	4,983	125	1,699	1,698	6,446	831,427	852,858	Kdu-gl 465 to 469 merged into one

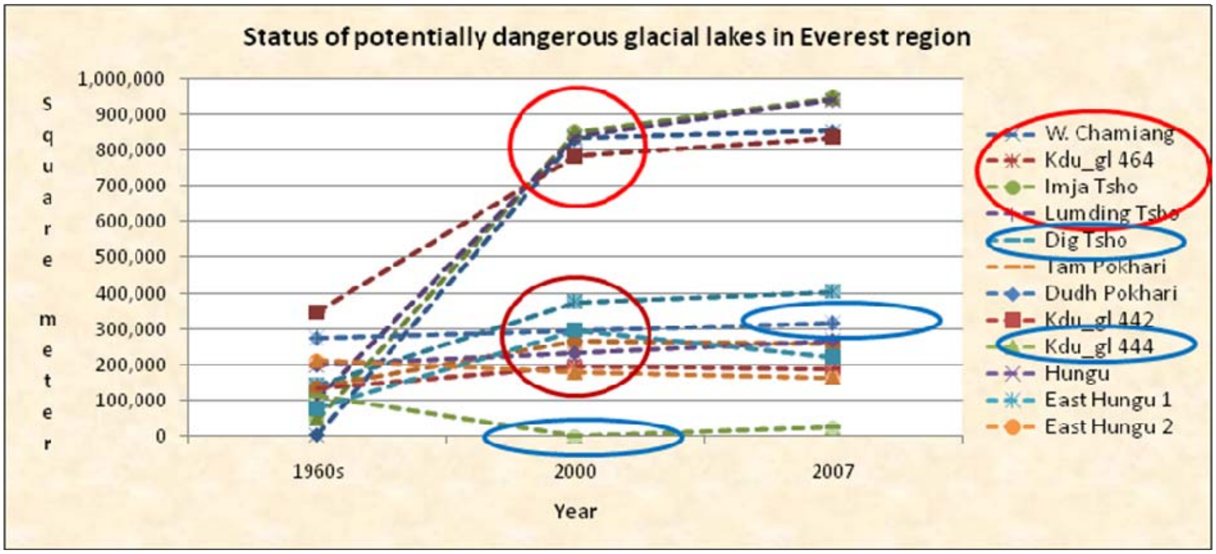


Figure 5: Status of potentially dangerous glacial lakes of Everest region

The Lake Kdu_gl 444 is located at 27°48'15"N and 86°56'37"E in the Hungu valley at an altitude of 5,056 masl. The lake area was 112,398 sq m with the average length of 420m when it was identified as a potentially dangerous glacial lake in 2000 (Mool et al. 2001). In the satellite image of 2001 the lake was completely dried or drained and again it appeared in 2007 with the size of 25,376 sq m. The lake is a valley lake and away from the glacier, it could not be a dangerous lake. Compared to the potentially dangerous lakes in the Dudh Koshi basin the area of Lake 444 is very small to include in the list of the potentially dangerous lake hence it can be removed from the list.

The Lake Dig Tsho at location of 27° 52’ 25”N and 86° 35’ 37”E in the Langmoche valley is at an altitude of 4,365 masl. The lake had an outburst event in 1985. After the outburst the lake area was reduced to 0.3 sq km with maximum depth of less than 10m. The lake is surrounded by thick moraine in two sides and steep sloping Langmoche glacier in western side and lake out let to eastern side. From the analysis of temporal satellite images and field observations show that the extreme end of the lake has reached the steep snout of Langmoche Glacier and there is no possibility of further expansion of the lake. The present outlet of the lake is at the same level as the Langmoche river bed (Figure 3). From which it can be concluded that Dig Tsho is no longer a potentially dangerous lake as was identified in the 2001 inventory by ICIMOD and UNEP.

a. Dig Tsho Glacial lake in April 2008

b. Outlet of Dig Tsho and Langmoche riverbed

Figure 6: The Lake Dig Tsho is no longer danger as the lake outlet and river bed is at the same level

Glacial lake outburst floods

Due to the faster rate of ice and snow melting, water accumulating rapidly in the lake behind the loose moraine. The increase in water volume in the lake increases the potential energy reducing the shear strength of the damming material. Ultimately the loose moraine dam has to breach out to release the water. Sudden discharge of large volume of water with debris from these lakes causes glacial lake outburst flood (GLOF). The GLOF in the downstream valley resulted serious death tolls and destruction of valuable natural resources such as forests, farmlands and costly mountain infrastructures. A number of Glacial Lake Outburst Flood (GLOF) events have been reported in this region, some of which have trans-boundary effects. With the increasing trend of glacier retreat; the formation, merging and enlarging of glacial lakes are now more prominent with the potential threat of GLOF. However, the potentially dangerous lakes are situated in remote areas, if the danger from these lakes known in advance, the GLOF risk could be reduced by saving life and property of communities living at downstream.

A number of GLOFs have recorded in this basin. The Nare GLOF happened in 1977, the Dig Tsho GLOF was experienced in 1985, the Tam Pokhari GLOF took place in 1998 and a GLOF from Lake Kdu_gl 458/459 (associated with glacier Kdu_gr 260) was also inferred from satellite imageries. These GLOF events have caused extensive damage to roads, bridges, trekking trails, and villages, as well as loss of human life and other infrastructure.

Dig Tsho GLOF: The Dig Tsho GLOF was triggered by an ice avalanche from the Langmoche glacier which induced a dynamic wave on the lake. Vuichard and Zimmerman (1987) reported that an ice mass of 100 to 200 thousand m^3 dislodged itself from the overhanging glacier tongue and plunged into the lake. According to this report, the flood began in the early afternoon and lasted for 4–6 hours. They also estimated that the peak flood was 1600 m^3s^{-1}, but Cenderelli and Wohl (2001) estimated a much higher peak discharge of 2350 m^3s^{-1}.

Local witnesses reported that the flood surge front moved rather slowly down the valley as a huge black mass of water and debris. The mean velocity of the surge front was 4-5 m^3s^{-1} (Vuichard and Zimmermann 1987). In some places, people were able to cross the river over suspension bridges whilst the water rushed below. Multiple surges were also reported, for example, the bridges at Jorsalle, Phakding, and Jubing villages were not destroyed until 30–90 minutes after the passage of the initial surge. The most significant impact of the GLOF was the complete destruction of the newly built hydropower station at Thamo village. The consequences of this GLOF were devastating, both socially and economically. Individual families directly hit by the surge lost their property and holdings, houses, and cattle. About 30 houses in the village were reported to be lost; in a few cases the properties could be salvaged, but this was more the exception than the rule. Villagers lost their subsistence base as well since their cultivable land and forest were also destroyed. Moreover, the tourist economy was affected because tea stalls and lodges were cut off due to the destruction of trails and bridges. About 14bridges from Mingbo to Jubing village were washed away by the surge.

The past record shows at least one GLOF event happens at an interval of 3 to 10 years in the Himalayan region but with the increased pace of global warming and climate variability in the recent decade the increase in frequency of GLOF events in coming years is anticipated.

CONCLUSIONS

The Dudh Koshi basin is the largest glaciated basins in Nepal. The basin consist altogether 278 glaciers and out of which 40 are valley glaciers covering more than 70% in area. In the context of global warming almost all the glaciers snout are retreating at the rate 10 to 59 m/yr. The Imja glacier is one of the fastest glacier retreating since 2000 at the rate of 74m/year and estimating 100m/yr in coming years.

The fast and continuous retreat of glaciers resulted in the proliferation of 34 major glacial lakes and 24 new at an elevation between 4,349 and 5,636 masl. The basin is already threatened by 12 potentially dangerous glacial lakes however from the field experiences two of it can be removed from the list. The rapid growing glacial lakes may pose danger in future hence the knowledge in growth of glacial lakes enlighten the importance of monitoring of glaciers and glacial lakes for the sound management of water resources and disaster risk reduction. However, the study of this phenomenon is a challenge with the limits imposed by the higher altitude, the rarefied atmosphere, the remoteness of many of the locations and the short mapping season.

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