Glaciers, glacial lakes and glacial lake outburst floods in the Mount Everest region, Nepal

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ABSTRACT. Recent climate changes have had a significant impact on the high-mountain glacial environment. Rapid melting of glaciers has resulted in the formation and expansion of moraine-dammed lakes, creating a potential danger from glacial lake outburst floods (GLOFs). Most lakes have formed during the second half of the 20th century. Glaciers in the Mount Everest (Sagamartha) region, Nepal, are retreating at an average rate of 10–59 m a^{-1}. From 1976 to 2000, Lumding and Imja Glaciers retreated 42 and 34 m a^{-1}, respectively, a rate that increased to 74 m a^{-1} for both glaciers from 2000 to 2007. During the past decade, Himalayan glaciers have generally been shrinking and retreating faster while moraine-dammed lakes have been proliferating. Although the number of lakes above 3500 m a.s.l. has decreased, the overall area of moraine-dammed lakes is increasing. Understanding the behaviour of glaciers and glacial lakes is a vital aspect of GLOF disaster management.

INTRODUCTION

Dudh Koshi basin in eastern Nepal is one of the country's largest and most important basins in terms of glaciers and glacial lakes, and probably the most densely glacierized region of Nepal (Bajracharya and others, 2007). The glaciers extend to latitude 27°38′05″ N and 4206 m a.s.l., although the termini of most are at about 5000 m a.s.l. The largest glacier in this basin is Ngojumba Glacier with an area of 82.61 km^2; however, the largest glacier in Nepal is Kanchenjunga Glacier with an area of 94.52 km^2. Changes in mountain glaciers are among the best natural indicators of climate change (Oerlemans, 1994; Houghton and others, 2001) and there has been a significant impact on this high-mountain glacial environment. The glaciers are melting rapidly (Fujita and others, 2001), leading to the formation of new glacial lakes, the expansion of existing moraine-dammed lakes and the potential for glacial lake outburst floods (GLOFs) (Watanabe and others, 1994). Most of the lakes, above 3500 m a.s.l., formed in response to warming temperatures during the second half of the 20th century (Yamada and Sharma, 1993; Mool and others, 2001). The largest of the lakes is Imja Tsho with an area of about 0.95 km^2, recorded as one of the fastest-growing lakes in the entire Himalaya (Bajracharya and others, 2007). Understanding the response of glaciers and glacial lakes to rising temperatures is an essential aspect of planning water resources as well as managing the potential for GLOF disasters.

METHODS

The threshold ratio from Thematic Mapper (TM) band 4 and 5 images has been used widely for glacier delineation. This technique is simple, robust and accurate and has been applied to the 2000 Swiss glacier inventory and others (Sidjak and Wheate, 1999; Albert, 2002; Paul, 2002; Paul and others, 2004; Bolch and others, 2008). Although the overall delineation of glaciers was carried out using this method, manual digitizing of sources from different years was used for the specific analysis of glacier change presented here: topographic maps (1960s), Landsat Multispectral scanner (MSS) (1976), Landsat TM (1992), Landsat Enhanced TM Plus (ETM+) (2001) and Advanced Land Observing Satellite (ALOS) (2007). Due to limitations in the remote-sensing imagery (e.g. shadows, coarse resolution), the number of valley glaciers studied to identify their retreat rate was limited to 22. Glacier length was obtained in the geo-referenced images from the difference between the highest and lowest elevations. As it was difficult to identify the smaller lakes in the coarse-resolution satellite images (Bolch and others, 2008), the number of small erosion and supraglacial lakes decreased significantly compared with the 1960s. However, the area of Imja Tsho, derived from a manual delineation based on the 2000 Landsat scene, was 0.77 km^2, whereas its area derived from a classification of the same Landsat scene was 0.766 km^2 (Bolch and others, 2008), indicating some consistency between the two methods.

GLACIERS AND GLACIER RETREAT

The number of glaciers mapped in the basin was 278 with a total area of 482 km^2 and an ice volume of 51 km^3 (Mool and others, 2001). Although they are located in the high mountains (Fig. 1), 40 glaciers, accounting for 70% of the glacierized area, extend down into the valley. Ngojumba, Khumbu, Bhote Koshi and Hungu glaciers are the principal glaciers in the Dudh Koshi basin and have areas of 82.61, 45.39, 35.63 and 22.91 km^2, respectively. The average minimum retreat rate was 10 m a^{-1}, observed on Langdak, West Lhotse, Lhotse and Setta glaciers. Imja Glacier retreated at 34 m a^{-1} from 1962 to 2000, a rate that increased to 74 m a^{-1} from 2000 to 2007, giving an overall average retreat rate of 59 m a^{-1}; it is now one of the fastest-retreating glaciers in the Himalaya. Other rapidly retreating glaciers are West Chamiang and Ombigaichain (Table 1; Fig. 2). In general, glaciers have been shrinking and retreating faster in the present decade (2000–07); Khromova and others, 2003; Paul and others, 2004).

GLACIAL LAKES AND LAKE ACTIVITY

There are 473 glacial lakes >0.003 km^2 situated above 3500 m a.s.l. in the Dudh Koshi basin (Mool and others,

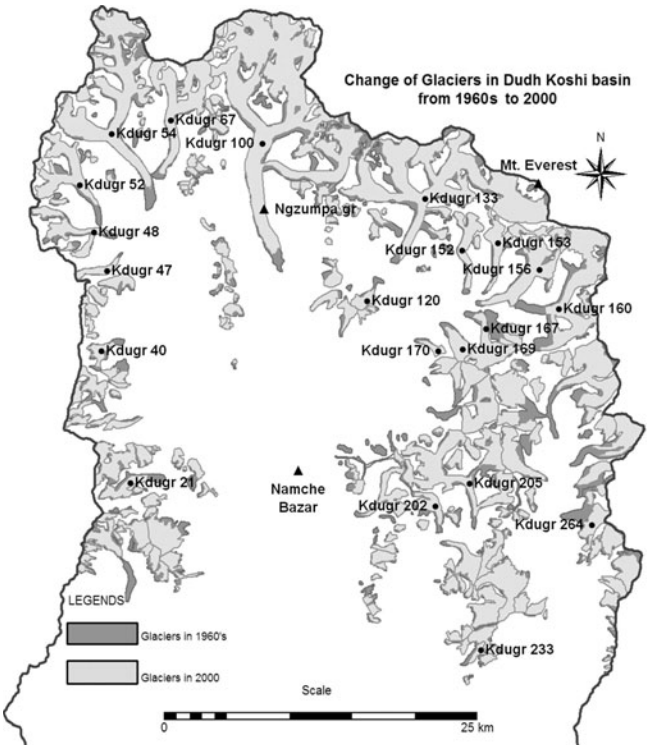

Fig. 1. Change in glaciers in the Dudh Koshi basin from the 1960s to 2000.

2001). The most important of these are Lumding Tsho, Dig Tsho, Imja Tsho, Tam Pokhari, Dudh Pokhari, Hungu and Chamiang.

In a recent study, Bajracharya and Mool (2005) mapped 296 lakes from 2001 Landsat ETM+. They found that the lakes that had disappeared were mostly the supraglacial and erosion lakes. Most of the former were either too small to map (Bolch and others, 2008) or had disappeared; some had been transformed into moraine-dammed lakes. While there had been a 37% decline in the number of lakes, the total area of lakes increased by 21%, due to the proliferation of moraine-dammed lakes. Of the major lakes (defined as >0.02 km^2), 34 were increasing in size and 24 new ones had appeared. The latter consisted of 15 moraine-dammed lakes, five supraglacial lakes, two valley lakes (lakes in the flood plain) and two erosion lakes (lakes on the valley slopes) (Table 2). Areas of these major glacial lakes, which lie at 4349–5636 m a.s.l., ranged from 0.021 to 0.848 km^2.

The fast and continuous retreat of glaciers and growth of glacial lakes highlights the need to monitor glaciers and glacial lakes for the sound management of water resources. However, study of this phenomenon is a challenge because of the limits imposed by high altitude, the rarefied atmosphere, the remoteness of many of the locations and the short mapping season.

This is partly reflected in Table 3 which shows the growth rate of the lakes. From 2000 to 2007 the values are mostly negative because the image used for the analysis was from January 2007, a time of the year when most of the lakes at high altitude are frozen and at their minimum extent; however, some (e.g. lakes 71 and 543) showed significant growth.

Table 1. Retreat rate of valley glaciers in the Dudh Koshi basin

Glacier No.	Glacier name	Elevation range	Mean glacier length in year					Average retreat rate	
			1960s*	1976	1992	2000	Jan. 2007	1976–2000	2000–07
		m a.s.l.	m	m	m	m	m	m a^{-1}	m a^{-1}
21	Lumding	5944–4846	6015	5715	4884	4700	4255	42	74
40	Langmuche	5669–4389	3160	2711	2711	2388	2388	13	0
47	Langdak	5883–4816	4430	4237	4237	4028	3764	9	44
48	Chhule	5974–4816	7600	7352	7352	6818	6658	22	27
52	Melung	5944–4926	8870	7805	7430	7430	7378	16	9
54	Bhote Koshi	6450–4755	17 100	16 855	16 785	16 455	NA	17	NA
67	Lumsamba	6919–4907	9500	9421	9197	8955	NA	19	NA
100	Ngojumba	7897–4511	22 500	21 975	21 925	21 625	21 543	15	14
120	Cholo	5151–4511	2520	2339	1756	1586	1293	31	49
133	Khumbu	8230–4816	12 040	11 681	11 343	11 198	11 097	20	17
152	Nuptse	5791–4907	6330	6207	6022	5898	NA	13	NA
153	W. Lhotse	5761–4938	4110	3908	3838	3722	3722	8	0
156	Lhotse	6160–4770	8870	8733	8626	8453	8335	12	20
160	Imja	7864–4999	10 770	9242	8988	8430	7986	34	74
166	Ombigaichain	6200–4816	4110	3328	3117	2123	2033	50	15
167	Amadablam	5425–4679	5060	4951	4911	4311	NA	27	NA
169	Duwo	5273–4465	2530	2446	2357	2056	NA	16	NA
170	Tsuro	6779–4298	2215	2087	2066	1811	NA	12	NA
186	Kyashar	6523–4846	6330	Shadow	6042	5797	5662	NA	23
205	Inkhu	5029–4511	10 770	10 610	10 347	9786	9721	34	11
233	233	7319–4968	1900	1589	1487	1259	NA	14	NA
264	W. Chamiang	5944–4846	3800	2573	2108	1558	1433	42	21

*1960s data are from topographic maps published by the Survey of India;.
NA: not available.

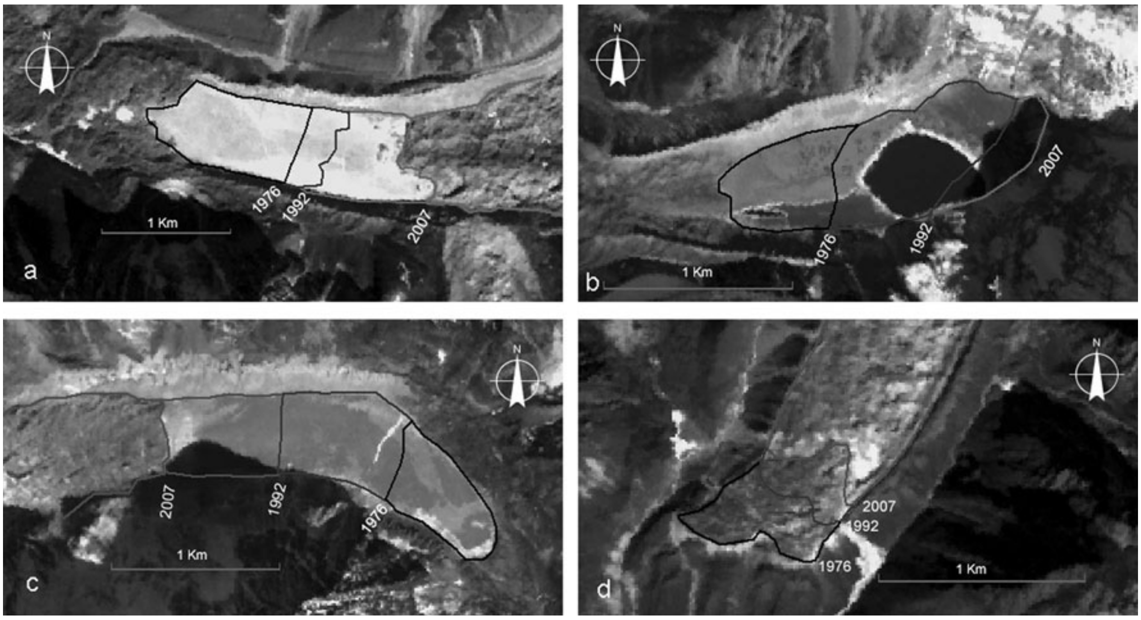

Fig. 2. Examples of glacier retreat and lake expansion from the Dudh Koshi basin: (a) Imja Glacier and Tsho; (b) glacier 262 (lake 464) in Hungu valley; (c) Lumding Glacier and Tsho; (d) Khumbu Glacier.

POTENTIALLY DANGEROUS GLACIAL LAKES

Rapid retreat of glaciers increases run-off, contributes to the growth of glacial lakes and converts some supraglacial lakes to moraine-dammed lakes (Hambrey and others, 2008). These lakes tend to breach the weak and unstable loose moraine dam (Yamada and Sharma, 1993; Watanabe and others, 1995), with catastrophic impacts downstream. Amongst the numerous glaciers and glacial lakes, the basin includes 12 potentially dangerous glacial lakes, the largest number in any sub-basin of Nepal, all of which (except lake 444) are dammed by loose and unstable moraine. Of the potentially dangerous glacial lakes identified (Table 4), three (lakes 422, 442 and 462) have remained at approximately the same size, one (lake 444) dried up in 2001 but subsequently reappeared, Tam Pokhari (lake 399) and Dig Tsho (lake 55) have a GLOF history, while the remaining six lakes (28, 350, 449, 459, 464 and 466) are growing. Imja Tsho (lake 350) is one of the fastest-growing lakes in the Himalaya.

Lake 444 was identified by Mool and others (2001) as a potentially dangerous glacial lake in 2000, but later that year had dried up or completely drained, reappearing again in 2007 (Bajracharya and others, 2007) with an area of 25 376 m^2 (Table 4). It is a valley lake separated from the glacier. The risk of a GLOF from lake 444, compared with other lakes in the Dudh Koshi basin is considered to be sufficiently small that it should be removed from the list.

Dig Tsho (lake 55) had an outburst event in 1985 after which the lake area was reduced to 0.3 km^2 with maximum depth >10 m (more details are given below). The lake is surrounded by thick moraine on two sides, the steep-sloping Langmoche Glacier to the west and the lake outlet to the east. Analysis of temporal satellite images and field observations shows that the extreme end of the lake abuts the steep snout of Langmoche Glacier and there is no possibility for further expansion of the lake. As the present lake outlet is at the same level as the bed of the Langmoche river (Fig. 3), it can be concluded that Dig Tsho is no longer a potentially dangerous lake, as indicated in the 2001 inventory by the International Centre for Integrated Mountain Development (ICIMOD) and United Nations Environment Programme (UNEP).

GLACIAL LAKE OUTBURST FLOODS

Fast glacier retreat during the past decade has resulted in the rapid accumulation of meltwater in most of the moraine-dammed lakes in the basin, has increased their potential energy and reduced the shear strength of the damming material. Ultimately the loose-moraine dam will be breached, causing a GLOF (Ives, 1986; Zimmermann and others, 1986; Yamada, 1998; Richardson and

Table 2. State of glacial lakes in the Dudh Koshi basin (1960–2000)

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

Table 3. Activity of glacial lakes in the Dudh Koshi basin

Lake No.	Location	Type	Average area in year			Distance to glacier	Average growth rate	
			1960s	2000	2007		1960s–2000	2000–07
			m^2	m^2	m^2	m	%	%
40	27°47′44′N, 86°37′14′E	Moraine-dammed	18 914	23 289	22 319	270	23	–4
41	27°47′41′N, 86°37′36′E	Moraine-dammed	26 289	74 197	92 951	785	182	25
43	27°47′09′N, 86°38′06′E	Moraine-dammed	13 662	25 888	26 721	70	89	3
47	27°49′14′N, 86°35′38′E	Blocked	12 866	35 593	Shadow	45	177	NA
52	27°49′38′N, 86°34′38′E	Moraine-dammed	2096	30 921	33 131	785	1375	7
69	27°57′06′N, 86°34′44′E	Supraglacial	3316	23 322	19 168	0	603	–18
71	27°56′39′N, 86°33′15′E	Supraglacial	4404	21 194	54 101	300	381	155
160	27°57′38′N, 86°39′58′E	Erosion	15 439	27 473	24 488	670	78	–11
229	27°56′03′N, 86°44′42′E	Erosion	17 933	20 184	22 210	515	13	10
255	27°57′23′N, 86°48′37′E	Supraglacial	10 425	48 496	12 284	0	365	–75
286	27°59′36′N, 86°50′30′E	Supraglacial	6765	22 191	13 659	0	228	–38
287	27°59′51′N, 86°50′20′E	Supraglacial	48 811	121 762	121 999	0	149	0
300	27°57′38′N, 86°50′06′E	Block/valley	16 606	23 474	22 110	95	41	–6
342	27°55′08′N, 86°54′50′E	Supraglacial	6977	41 503	9144	0	495	–78
384	27°53′09′N, 86°50′50′E	Moraine-dammed	14 431	29 750	23 711	245	106	–20
446	27°49′58′N, 86°55′18′E	Moraine-dammed	207 314	349 263	357 903	0	68	2
472	27°42′40′N, 86°58′48′E	Moraine-dammed	6526	46 215	49 900	0	608	8
483	27°43′39′N, 86°34′22′E	Moraine-dammed	New	34 016	32 040	0	NA	–6
491	27°46′39′N, 86°38′44′E	Moraine-dammed	New	286 119	305 913	245	NA	7
495	27°54′32′N, 86°35′00′E	Moraine-dammed	New	20 044	23 582	405	NA	18
501	27°57′30′N, 86°39′50′E	Moraine-dammed	New	60 039	38 937	270	NA	–35
502	27°59′20′N, 86°39′06′E	Moraine-dammed	New	58 097	55 811	0	NA	–4
505	27°56′10′N, 86°42′48′E	Supraglacial	New	48 184	56 412	0	NA	17
511	27°59′27′N, 86°41′38′E	Supraglacial	New	27 858	18 444	0	NA	–34
513	28°02′30′N, 86°42′31′E	Moraine-dammed	New	38 349	32 060	210	NA	–16
517	27°48′38′N, 86°50′52′E	Moraine-dammed	New	69 238	66 056	0	NA	–5
521	27°53′13′N, 86°54′01′E	Moraine-dammed	New	65 368	59 541	0	NA	–9
522	27°53′00′N, 86°53′43′E	Moraine-dammed	New	22 274	13 317	135	NA	–40
524	27°42′49′N, 86°55′12′E	Moraine-dammed	New	67 607	66 011	310	NA	–2
526	27°43′28′N, 86°54′13′E	Moraine-dammed	New	31 381	34 001	170	NA	8
528	27°49′26′N, 86°55′54′E	Moraine-dammed	New	46 225	36 571	880	NA	–21
536	27°58′08′N, 86°42′05′E	Supraglacial	New	27 084	19 604	0	NA	–28
543	27°45′57′N, 86°52′31′E	Supraglacial	New	21 467	44 821	0	NA	109

Notes: Due to different satellite images and projection parameters the accuracy of the data varies from 90 to 95%,. NA: not available.

Table 4. Status of potentially dangerous glacial lakes in the Dudh Koshi basin in 2007

Lake No.	Name	Location	Altitude	Average length in year			Average area in year			Remarks
				1960s	2000	2007	1960s	2000	2007	
			m a.s.l.	m	m	m	m^2	m^2	m^2	
28	Lumding Tsho	27°46.51′ N, 86°37.53′ E	4846	625	1952	2180	104 944	836 765	940 077	Growing
55	Dig Tsho	27°52.41′ N, 86°36.61′ E	4364	605	1262	1263	143 250	375 681	403 044	GLOF on 4 Aug. 1985, no danger
350	Imja Tsho	27°54.00′ N, 86°55.40′ E	5023	410	1822	2027	48 811	848 742	945 662	Rapidly growing
399	Tam Pokhari	27°44.33′ N, 86°50.76′ E	4431	515	925	898	138 846	265 386	255 495	GLOF on 3 Sep. 1998
422	Dudh Pokhari	27°41.21′ N, 86°51.68′ E	4760	1120	1095	1159	274 297	297 574	316 767	No change in area
442	Unnamed	27°47.70′ N, 86°54.81′ E	5266	840	1082	1075	133 753	194 966	188 559	No change in area
444	Unnamed	27°48.23′ N, 86°56.61′ E	5056	420	0	235	112 398	0	25 376	Dried/reappeared, no danger
449	Hungu	27°50.17′ N, 86°56.26′ E	5181	875	1054	1327	198 905	232 842	267 720	Merged with lake 532
459	East Hungu 1	27°47.92′ N, 86°57.95′ E	5379	465	982	1105	78 761	296 886	222 102	Merged with lake 460
462	East Hungu 2	27°48.30′ N, 86°58.65′ E	5483	640	448	459	211 877	178 317	164 098	Area decreasing
464	Unnamed	27°46.86′ N, 86°57.22′ E	5205	1100	1918	2251	349 397	783 553	835 131	Growing in size
466	W. Chamiang	27°45.24′ N, 86°57.33′ E	4983	125	1699	1698	6446	831 427	852 858	465–469 merged into one

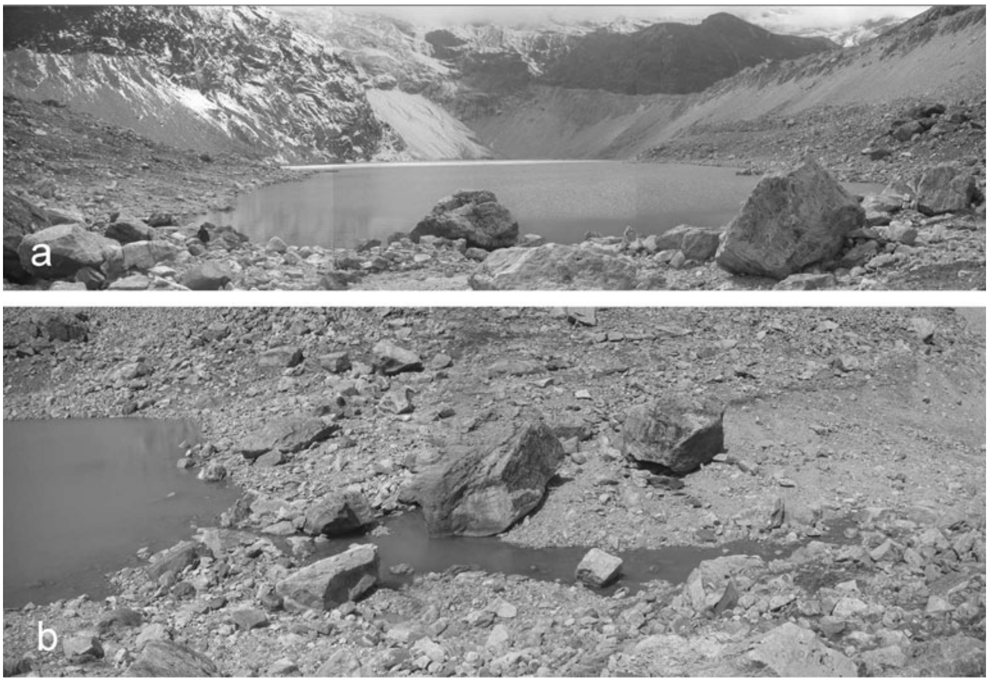

Fig. 3. Dig Tsho is no longer a threat, as the lake outlet and river bed are at the same level. (a) Dig Tsho in April 2008. (b) Outlet of Dig Tsho and Langmoche river bed.

Reynolds, 2000; Mool and others, 2001; Kattelmann, 2003). A number of GLOFs have already been reported in this region (Yamada and Sharma, 1993; Mool, 1995; Reynolds, 1998; Yamada, 1998, 2000; Mool and others, 2001; Bajracharya and others, 2007), such as the Nare GLOF (1977), the Dig Tsho GLOF (1985), the Tam Pokhari GLOF (1998) and one from lake 458/459 (associated with glacier 260) inferred from satellite imagery.

Only the Dig Tsho GLOF is well documented. Vuichard and Zimmermann (1987) reported that a $10–20 \times 10^4\,m^3$ ice mass dislodged itself from the overhanging Langmoche Glacier and plunged into the lake, inducing a dynamic wave. The flood began in the early afternoon and lasted for 4–6 hours. The peak flood was estimated at $1600\,m^3\,s^{-1}$, but Cenderelli and Wohl (2001, 2003) consider the peak discharge to be of the order of $2350\,m^3\,s^{-1}$. The mean velocity of the surge front was $4–5\,m^3\,s^{-1}$ (Vuichard and Zimmermann, 1987). Multiple surges were also reported; for example, the bridges at the villages of Jorsalle, Phakding and Jubing were not destroyed until 30–90 min after the passage of the initial surge. The most significant impact of this GLOF was the complete destruction of a new hydropower station at Thamo and about 30 houses, and the loss of 14 bridges between Mingbo and Jubing. The social, economic and environmental consequences of this GLOF were devastating. Because of the destruction of forest and inundation of cultivable land, villagers lost their subsistence base. The erosion from the surge along the river valley left active scars where further erosion was accelerated by wind, snow, rain and undercutting by the river. Even though Dig Tsho stabilized, the settlements, cultivated land and forests are still at threat from landslides and further erosion.

The past record shows that at least one GLOF event occurs every 3–10 years in the Himalayan region (Bajracharya and others, 2008), but with rising temperatures and more variability in the climate the frequency of GLOF events is expected to increase in the coming years.

CONCLUSIONS

The Dudh Koshi basin is the largest glacierized basin in Nepal. It has 278 glaciers of which 40, amounting to 70% of the area, are valley-type. Almost all the glaciers are retreating at rates of $10–59\,m\,a^{-1}$, but the rate for some has accelerated during the last half-decade to $74\,m\,a^{-1}$. This fast and continuous retreat of glaciers has resulted in a proliferation of major glacial lakes to 34 and the creation of 24 new ones at 4349–5636 m a.s.l. The basin is threatened by 12 potentially dangerous glacial lakes, but following further fieldwork two of these can now be removed from the list. Expanding glacial lakes may pose additional dangers in the near future, so adequate monitoring of glaciers and their lakes is vital for the sound management of water resources and disaster mitigation. A major challenge is how to accomplish this, considering the limits imposed by high altitude, the rarefied atmosphere, the remoteness of most locations and the short mapping season.

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