Glacial Lakes in the Dudh Koshi Sub-basin of Nepal and Pho Chu Sub-basin of Bhutan

Glacial lakes are formed when the glacier ice melts. Most present-day large glacial lakes are end-moraine lakes that have grown from small supraglacial lakes. Some of the lakes that have been studied in detail from the beginning of the lake formation show that the rate of lake extension is directly proportional to glacier retreat.

A study carried out by ICIMOD (1999–2001) identified the glacial lakes larger than 0.003 sq.km situated above an altitude of 3500m and reported 2323 lakes in Nepal and 2674 lakes in Bhutan (Mool et al. 2001a, b). These data were based mainly on topographic maps from the early 1960s. Over the past 40 years, the glaciers have been retreating with a resulting increase in the size of associated glacial lakes. Each lake larger than 0.02 sq.km contains at least 6×10^5 m^3 of water; if it breaches, downstream valleys could suffer hazardous consequences. Therefore, these are defined hereafter as 'major' glacial lakes. Monitoring these lakes, both by remote sensing and field verification, is the important groundwork needed for planning and implementing mitigative measures and installing early warning systems. Case studies of glacial lakes in the Dudh Koshi sub-basin of Nepal and Pho Chu sub-basin of Bhutan are presented below.

Glacial lakes of the Dudh Koshi sub-basin of Nepal

The Dudh Koshi sub-basin is the largest basin in Nepal. In terms of glacial lakes, it is perhaps the most densely glaciated region of the country (Bajracharya et al. 2004; Figure 3.1). Mool et al. (2001a) mapped 473 glacial lakes in this region using archival data from the 1960s, but by 2006 only 296 could be re-identified using NaturalVue images from EarthSat (Table 3.1). Of the 177 lakes that disappeared most were erosion lakes, the remainder being either supraglacial lakes or moraine-dammed lakes.

Over time, erosion lakes dry up, and supraglacial lakes are transformed into moraine-dammed ones. Their number has decreased drastically (by approximately 37 per cent), while the lakes associated with glaciers have increased in size by 21 per cent (Table 3.1). Most of the supraglacial lakes have either disappeared or been transformed into moraine-dammed lakes. 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 (Table 3.2). Among these newly formed lakes are 15 moraine-dammed lakes, five supraglacial lakes, two valley lakes and two erosion lakes (Table 3.3). The areas of the major glacial lakes range from 0.021 sq.km to 0.848 sq.km, at altitudes of between 4,349 and 5,636m.

Figure 3.1: Glacial lakes in the Dudh Koshi sub-basin in 2001
(Note: the numbering of lakes starts from the outlet of the major stream and proceeds clockwise round the basin.)

Table 3.1: **Glacial lakes in the Dudh Koshi sub-basin (1960s and 2000)**							
Type of lake	**Number**			**Area ('000 m²)**			**Area of largest lake ('000 m²)**
	1960s	**2000**	**% change in number**	**1960s**	**2000**	**% change**	
Supraglacial (S)	267	72	-73	3,369	1,286	-62	121
Erosion (E)	141	98	-30	3,607	2,218	-39	356
Moraine-dammed (M)	33	89	170	2,291	7,254	217	848
Valley (V)	13	16	23	1,706	2,709	59	836
Blocked (B)	10	17	70	1,764	2,146	22	554
Cirque (C)	9	4	-56	335	226	-32	147
Total	473	296	-37	13,074	15,843	21	

Note: the conventional signs in the above table represent negative (-) for decrease in area and positive for increase in area.

B = main glacier blocking the branch valley; C = rounded, steep-walled in three sides;
E = formed at paleo-glacier area; M = dammed by end moraine; S = within glacier; V = along river valley

Impact of Climate Change on Himalayan Glaciers and Glacial Lakes

The Dudh Koshi basin has experienced a number of GLOF events in recent times: the Nare GLOF in 1977, the Dig Tsho GLOF in 1985, and the Tam Pokhari GLOF in 1998. A GLOF from Lake Kdu_gl 458/459 (associated with glacier Kdu_gr 260) was also inferred from satellite imagery of 2001. These GLOF events have caused extensive damage to roads, bridges, trekking trails, and villages, as well as loss of human life and other infrastructure (Fushimi et al. 1985; Galey 1985; Ives 1986; Vuichard and Zimmerman 1987). Despite numerous glacial lakes and past outburst floods, the basin still contains many potentially dangerous glacial lakes. In all likelihood, this basin will experience another GLOF event in the near future. While the basin is very remote and is located at an extreme elevation, as one of the most popular trekking routes in the Everest region it is nevertheless highly populated. Precisely because of the population density, it was singled out for potential GLOF hazard and risk assessment, and for hydrodynamic modelling.

Table 3.2: **Summary of activity of glacial lakes in the Dudh Koshi sub-basin (1960 –2000)**	
Disappeared (or less than 50×50 sq. m) lakes	**245**
Supraglacial lakes	199
Erosion lakes	34
Valley lakes	3
End moraine-dammed lakes	2
Lateral moraine dammed lakes	5
Cirque	2
Converted lakes	
(from supraglacial to end moraine-dammed)	**11**
New lakes	**24**
Supraglacial lakes	5
Erosion lakes	2
Valley lakes	2
End moraine-dammed lakes	15
Growing lakes	**34**
Supraglacial lakes	10
Valley lakes	2
End or lateral moraine-dammed lakes	17
Blocked lakes	2
Erosion lakes	3

Potentially dangerous glacial lakes in the Dudh Koshi sub-basin of Nepal

The Dudh Koshi basin contains twelve potentially dangerous glacial lakes, the largest number in any sub-basin of Nepal studied so far. All 12 potentially dangerous glacial lakes are moraine dammed lakes. The most well known lakes in this sub-basin are Lumding Tsho, Dig Tsho, Chokarma Cho, Imja Tsho, Tam Pokhari, Dudh Pokhari, Hungu, and Chamjang (Table 3.4). The Dig Tsho and Tam Pokhari lakes have experienced outburst events in the recent past. Field data indicate that Lake Dig Tsho is no longer dangerous and should be removed from the inventory. Three lakes: Kdu_gl 422, 442 and 462 have remained more or less the same size; a satellite image of 2001 showed that Lake Kdu_gl 444 no longer exists. In summary, of the twelve potentially dangerous glacial lakes listed in the Dudh Koshi sub-basin, two can be removed from the 'dangerous' list and four are more or less constant in size. The remaining six (Kdu_gl 28, 350, 449, 459, 464 and 466) are growing and expected to eventually breach.

Detailed studies of Lakes Dig Tsho and Imja Tsho

Lake Dig Tsho was at one time a 'potentially dangerous' glacial lake and did suffer a GLOF event in 1985. Lake Imja Tsho is a similar but much larger and rapidly growing lake in the same area. These two lakes share much of the same downstream terrain. The similarity between them means that information gathered from Lake Dig Tsho can be used to model and possibly predict how events may unfold at Lake Imja Tsho. These two lakes are discussed below in detail.

Table 3.3: **Activity of glacial lakes in association with glaciers in the Dudh Koshi sub-basin (1960s-2000)**

S.N.	Lake Number	Name/ Latitude, longitude	Type	Area (sq m) in 2000	Area (sq m) in 1960s	Associated glacier number	Distance to glacier (m)
1.	Kdu_gl 28	Lumding Tsho	M dammed	836,765	104,944	Kdu_gr 21	0
2.	Kdu_gl 40		M dammed	23,289	18,914	Kdu_gr 24	270
3.	Kdu_gl 41		M dammed	74,197	26,289	Kdu_gr 25	785
4.	Kdu_gl 43		M dammed	25,888	13,662	Kdu_gr 26	70
5.	Kdu_gl 47		Blocked	35,593	12,866	Kdu_gr 32	45
6.	Kdu_gl 52		M dammed	30,921	2,096	Kdu_gr 35	785
7.	Kdu_gl 55	Dig Tsho*	M dammed	375,681	143,250	Kdu_gr 40	0
8.	Kdu_gl 69		Supraglacial	23,322	3,316	Kdu_gr 48	0
9.	Kdu_gl 71		Supraglacial	21,194	4,404	Kdu_gr 49	300
10.	Kdu_gl 150		Erosion	25,489	16,394	x	x
11.	Kdu_gl 158	Tanjung Tsho	Valley	218,681	169,539	x	x
12.	Kdu_gl 160		Erosion	27,473	15,439	Kdu_gr 87	670
13.	Kdu_gl 163		M dammed	21,905	3,714	x	x
14.	Kdu_gl 168	Ngojumba Tsho	Valley	220,465	143,940	x	x
15.	Kdu_gl 177		Supraglacial	28,412	4,138	Kdu_gr 100	0
16.	Kdu_gl 222		Supraglacial	24,289	15,147	Kdu_gr 100	0
17.	Kdu_gl 229		Erosion	20,184	17,933	Kdu_gr 113	515
18.	Kdu_gl 255		Supraglacial	48,496	10,425	Kdu gr 130	0
19.	Kdu_gl 286		Supraglacial	22,191	6,765	Kdu_gr 133	0
20.	Kdu_gl 287		Supraglacial	121,762	48,811	Kdu_gr 133	0
21.	Kdu_gl 300	Paugungagayang	Block/valley	23,474	16,606	Kdu_gr 133	95
22.	Kdu_gl 340		Supraglacial	23,220	9,391	Kdu_gr 156	0
23.	Kdu_gl 342		Supraglacial	41,503	6,977	Kdu_gr 156	0
24.	Kdu_gl 350	Imja Tsho	M dammed	848,742	48,811	Kdu_gr 160	0
25.	Kdu_gl 384		M dammed	29,750	14,431	Kdu_gr 169	245
26.	Kdu_gl 387		Supraglacial	23,706	4,085	Kdu_gr 284	0
27.	Kdu_gl 399	Tam Pokhari*	M dammed	265,386	138,846	Kdu_gr 202	0
28.	Kdu_gl 442		M dammed	194,966	133,753	Kdu_gr 247	845
29.	Kdu_gl 446		M dammed	349,263	207,314	Kdu_gr 289	0
30.	Kdu_gl 449		M dammed	232,842	198,905	Kdu_gr 249	0
31.	Kdu_gl 459		M dammed	296,886	78,761	Kdu_gr 260	80
32.	Kdu_gl 464		M dammed	783,553	349,397	Kdu_gr 262	0
33.	Kdu_gl 466		M dammed	831,427	6,446	Kdu_gr 264	0
34.	Kdu_gl 472		M dammed	46,215	6,526	Kdu_gr 293	0
35.	Kdu_gl 483	27°43'39"N, 86°34'22"E	M dammed	34,016	New	Kdu_gr 3	0
36.	Kdu_gl 488	27°44'31"N, 86°40'24"E	Erosion	26,686	New	x	x
37.	Kdu_gl 489	27°44'42"N, 86°40'21"E	Erosion	34,246	New	x	x
38.	Kdu_gl 491	27°46'39"N, 86°38'44"E	M dammed	286,119	New	Kdu_gr 28	245
39.	Kdu_gl 495	27°54'32"N, 86°35'00"E	M dammed	20,044	New	Kdu_gr 46	405
40.	Kdu_gl 501	27°57'30"N, 86°39'50"E	M dammed	60,039	New	Kdu_gr 87	270
41.	Kdu_gl 502	27°59'20"N, 86°39'06"E	M dammed	58,097	New	Kdu_gr 90	0
42.	Kdu_gl 504	27°52'24"N, 86°41'17"E	Valley	32,090	New	x	x
43.	Kdu_gl 505	27°56'10"N, 86°42'48"E	Supraglacial	48,184	New	Kdu_gr 100	0
44.	Kdu_gl 511	27°59'27"N, 86°41'38"E	Supraglacial	27,858	New	Kdu_gr 100	0
45.	Kdu_gl 513	28°02'30"N, 86°42'31"E	M dammed	38,349	New	Kdu_gr 100	210
46.	Kdu_gl 517	27°48'38"N, 86°50'52"E	M dammed	69,238	New	Kdu_gr 208	0
47.	Kdu_gl 520	27°54'01"N, 86°54'45"E	M dammed	28,950	New	x	x
48.	Kdu_gl 521	27°53'13"N, 86°54'01"E	M dammed	65,368	New	Kdu_gr 282	0
49.	Kdu_gl 522	27°53'00"N, 86°53'43"E	M dammed	22,274	New	Kdu_gr 166	135
50.	Kdu_gl 524	27°42'49"N, 86°55'12"E	M dammed	67,607	New	Kdu_gr 240	310
51.	Kdu_gl 526	27°43'28"N, 86°54'13"E	M dammed	31,381	New	Kdu_gr 240	170
52.	Kdu_gl 528	27°49'26"N, 86°55'54"E	M dammed	46,225	New	Kdu_gr 287	880
53.	Kdu_gl 529	27°49'02"N, 86°56'26"E	Valley	31,838	New	x	x
54.	Kdu_gl 532	27°49'51"N, 86°56'14"E	M dammed	28,520	New	x	x
55.	Kdu_gl 533	27°49'15"N, 86°54'50"E	M dammed	25,197	New	Kdu_gr 288	95
56.	Kdu_gl 536	27°58'08"N, 86°42'05"E	Supraglacial	27,084	New	Kdu_gr 100	0
57.	Kdu_gl 539	27°55'20"N, 86°55'05"E	Supraglacial	34,459	New	Kdu_gr 156	0
58.	Kdu_gl 543	27°45'57"N, 86°52'31"E	Supraglacial	21,467	New	Kdu_gr 205	0

* Dig Tsho GLOF of 1985, Tam Pokhari GLOF of 1998, M: moraine, x: no data

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Lake ID	Name	Latitude (N)	Longitude (E)	Altitude (m)	Length (m) 1960s	Length (m) 2000	Area (sq m)** 1960s	Area (sq m)** 2000/01	Remark
Kdu_gl 28 (D)	Lumding Tsho	27° 46.51'	86° 37.53'	4,846	625	1952	104,944	836,765	Growing
Kdu_gl 350 (E)	Imja Tsho	27° 54.00'	86° 55.40'	5,023	410	1822	48,811	848,742	Rapid growth
Kdu_gl 399 (F)	Tam Pokhari	27° 44.33'	86° 50.76'	4,431	515	925	138,846	265,386	GLOF on 3 September 1998
Kdu_gl 422 (G)	Dudh Pokhari	27° 41.21'	86° 51.68'	4,760	1,120	1095	274,297	297,574	No change in area
Kdu_gl 442 (H)	Unnamed	27° 47.70'	86° 54.81'	5,266	840	1082	133,753	194,966	No change in area
Kdu_gl 444 (I)	Unnamed	27° 48.23'	86° 56.61'	5,056	420	–	112,398	–	Dried/breached
Kdu_gl 449 (J)	Hungu	27° 50.17'	86° 56.26'	5,181	875	1054	198,905	232,842	Merged with gl 532
Kdu_gl 459 (K)	East Hungu 1	27° 47.92'	86° 57.95'	5,379	465	1055	78,761	296,886	Possibly merged with 458 and 460
Kdu_gl 462 (L)	East Hungu 2	27° 48.30'	86° 58.65'	5,483	640	448	211,877	178,317	No change in area
Kdu_gl 464 (M)	Unnamed	27° 46.86'	86° 57.22'	5,205	1,100	1918	349,397	783,553	Growing
Kdu_gl 466 (N)	West Chamjang	27° 45.24'	86° 57.33'	4,983	125	1699	6,446	831,427	Kdu-gl 465 to 469 merged into one
Kdu_gl 55 (O)*	Dig Tsho	27° 52.41'	86° 36.61'	4,364	605	1262	143,250	375,681	GLOF on 4 August 1985, no danger

Table 3.4: **Potentially dangerous glacial lakes in the Dudh Koshi sub-basin**

* Based on field verification, Dig Tsho can be removed from the list of potentially dangerous lakes.
** Due to different map projections and sources used, the area of a lake may differ slightly.

Lake Dig Tsho

Dig Tsho glacial lake is located in the Langmoche Valley sub-basin of the Nangpo-Tsangpo area in the Bhote Koshi valley at 27° 52' 25"N latitude and 86º 35' 37"E longitude. Lake Dig Tsho is referenced as Kdu_gl 55. The lake is located at an altitude of 4,365m, and is fed by the steep Langmoche glacier (Figure 3.2). The Langmoche Glacier is a clean type glacier (referenced as Kdu_gr 40) that originates at 5,400m at the foot of the northeast face of Tangri Ragi Tau (6,940m) and is extensively nourished by snow avalanches. The glacier snout is exposed to heavy solar radiation, which has contributed to its rapid retreat and to the thinning of the snout in recent decades.

The lake is believed to have been full to its rim just before the outbreak on 4 August 1985. The centre of the lake was estimated to have been 20m deep (WECS 1987). The lake was dammed by a 60m high moraine assumed to have been formed during the Little Ice Age; the estimated composition of the moraine consisted of boulders (20 per cent), cobbles (25 per cent), gravel (40 per cent), sand and silt (15 per cent). The river valley and lake outlet consist mainly of boulders and cobbles (Figure 3.3).

Before its outbreak, Lake Dig Tsho had been impounded between well-developed end moraines and the receding Langmoche terminus. According to Vuichard and Zimmerman (1987), the maximum extent that the lake attained before the outbreak was 0.5 sq.km. The development of Lake Dig Tsho is analysed based on time series satellite images (Table 3.5 and Figures 3.4 and 3.5). The crescent shaped lake (of about 0.2 sq.km in size) already existed in the Corona image of December 1962. The lake had grown to 0.33 sq.km in 1975, and attained a maximum area of about 0.6 sq.km in 1983. This area is about 0.1 sq.km larger than suggested by Vuichard and Zimmerman (1987). The Landsat image of 1989, four years after the outburst, shows an area for Lake Dig Tsho of 0.3 sq.km — more or less the

Figure 3.2: Lake Dig Tsho in the foreground and Langmoche Glacier in the background (10 Oct 2006)

Figure 3.3: Outlet of Lake Dig Tsho after 1985 GLOF (10 Oct 2006)

Table 3.5: **Development of Lake Dig Tsho from 1962 to 2005**						
Fig	Year	Area (sq m)	Diff in area	Length (m)	Diff in length	
a.	1962	201,172		402		
b.	1975	334,861	133,689	669	267	0.32 km
c.	1983	597,923	263,062	1195	526	
d.	1989	315,865	-282,058	631	-564	
e.	1992	376,575	60,710	753	121	Outburst in 1985
f.	2000	361,867	-14,708	723	-29	
g.	2005	330,000		877		1.21 km
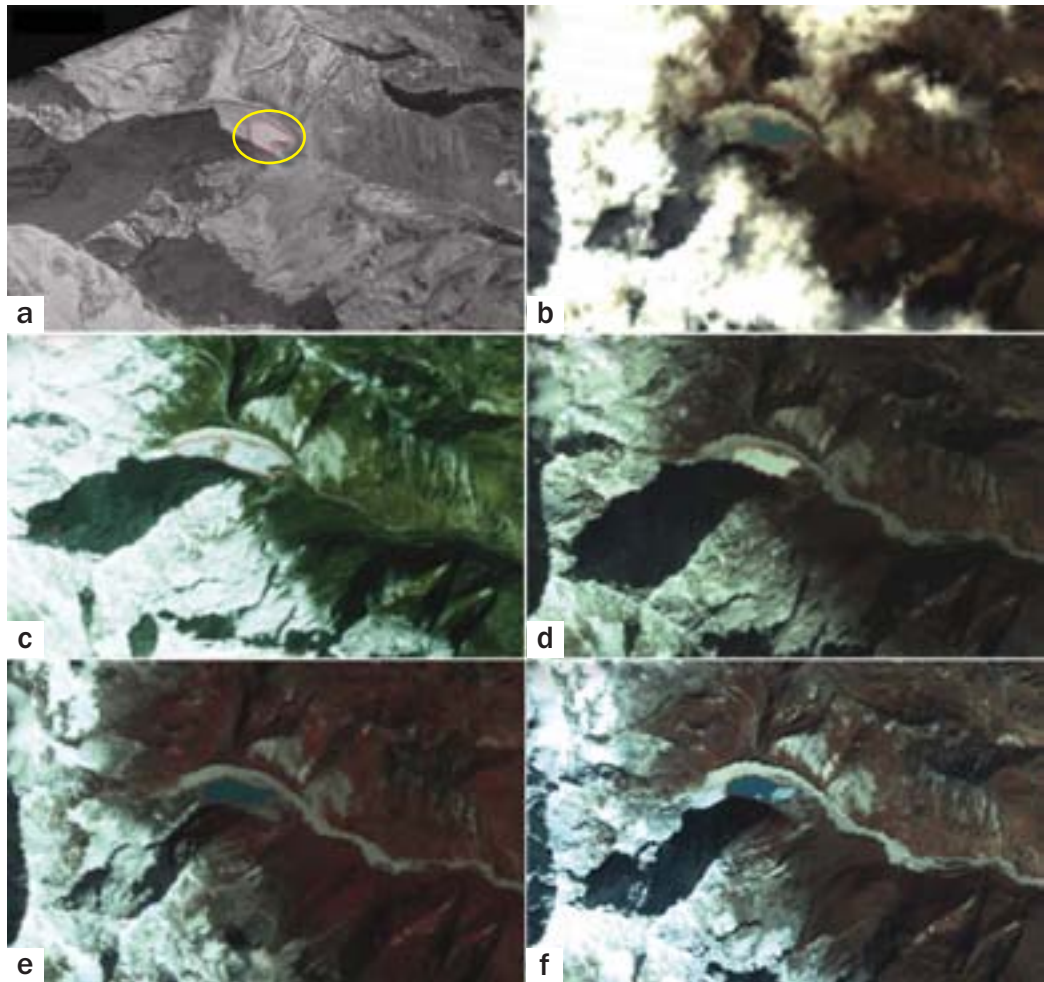
Figure 3.4: Lake Dig Tsho (D) in different satellite images taken between 1962 and 2000. Debris along the valley can be seen in the satellite images after 1985: a) Corona, 15 December 1962, b) Landsat MSS, 15 October 1975, c) Space Shuttle, 02 December 1983, d) Landsat5 TM, 11 December 1989, e) Landsat5 TM, 22 September 1992, f) Landsat7 etm+, 30 October, 2000

same as the 0.35 sq.km area reported in satellite images of 1992 and 2000, indicating stabilisation of the lake. The outer slope of the moraine dam is covered by vegetation while the inner slope is bare and unstable, a characteristic common to moraine dams. The stream draining out of Lake Dig Tsho is called Langmoche Khola, and is a tributary of the Bhote Koshi.

Dig Tsho GLOF of 1985

The Dig Tsho GLOF occurred on 4 August 1985 in the Dudh Koshi sub-basin. The event 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. By reconstructing the hydrograph they estimated that the peak flood had been 1600 m^3s^{-1}, but Cenderelli and Wohl (2001) estimated a much higher peak discharge of 2350 m^3s^{-1}.
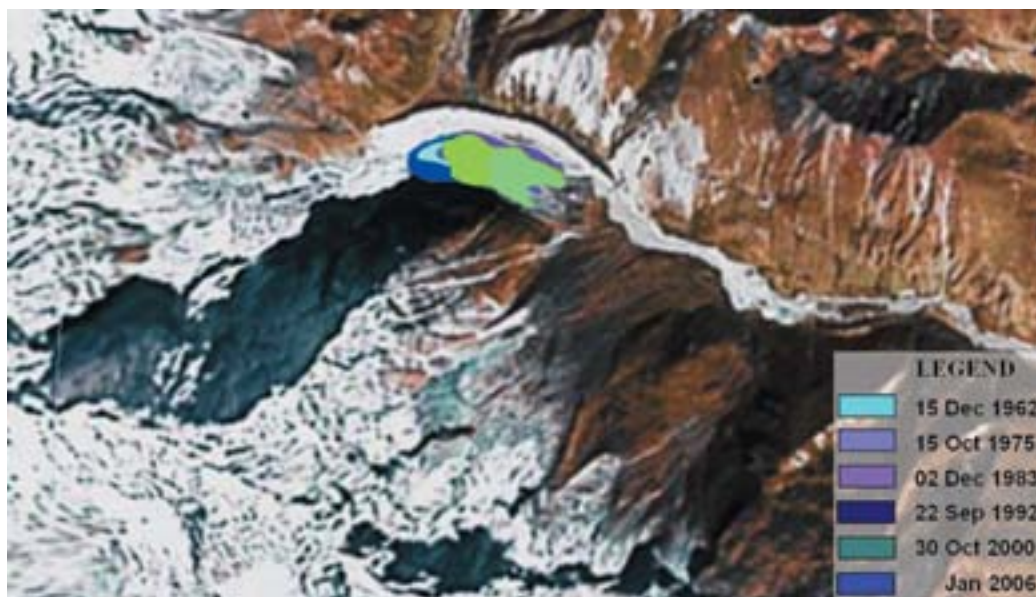
Figure 3.5: Development of Dig Tsho glacial lake between 1962 and 2005

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 m³s⁻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 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 Thame, (Figure 3.6) which had cost an estimated US $1.5 million.

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 14 bridges from Mingbo to Jubing village were washed away by the surge.

Figure 3.6: The Thame Hydropower Project a) before the GLOF (4 April 1985) and b) after the GLOF (10 October 1985)

Impact of Climate Change on Himalayan Glaciers and Glacial Lakes

Photos from a recent field study of the Lake Dig Tsho (Figure 3.7) reveal the following:

- Lake Dig Tsho shows evidence of past outburst events.
- The riverbed is composed mostly of boulders and cobbles.
- The lake is no longer hanging and the Langmoche River begins directly from the lake without any spillway.
- The Langmoche glacier (mother glacier of Lake Dig Tsho) is in a hanging position so avalanches or rock/ice falls cannot be discarded from the Langmoche glacier. Debris fall in the lake and possible splash of lake water overtopping the moraine could easily accommodate the debris flow as the outlet of the lake is wide enough.
- There is no indication of lateral moraine movement that could block the lake in the future.
- Available data shows no indication of lake growth since 1992. Further lake growth appears unlikely since the outlet is wide enough and the lake has extended down to the hard rock base glacier snout.
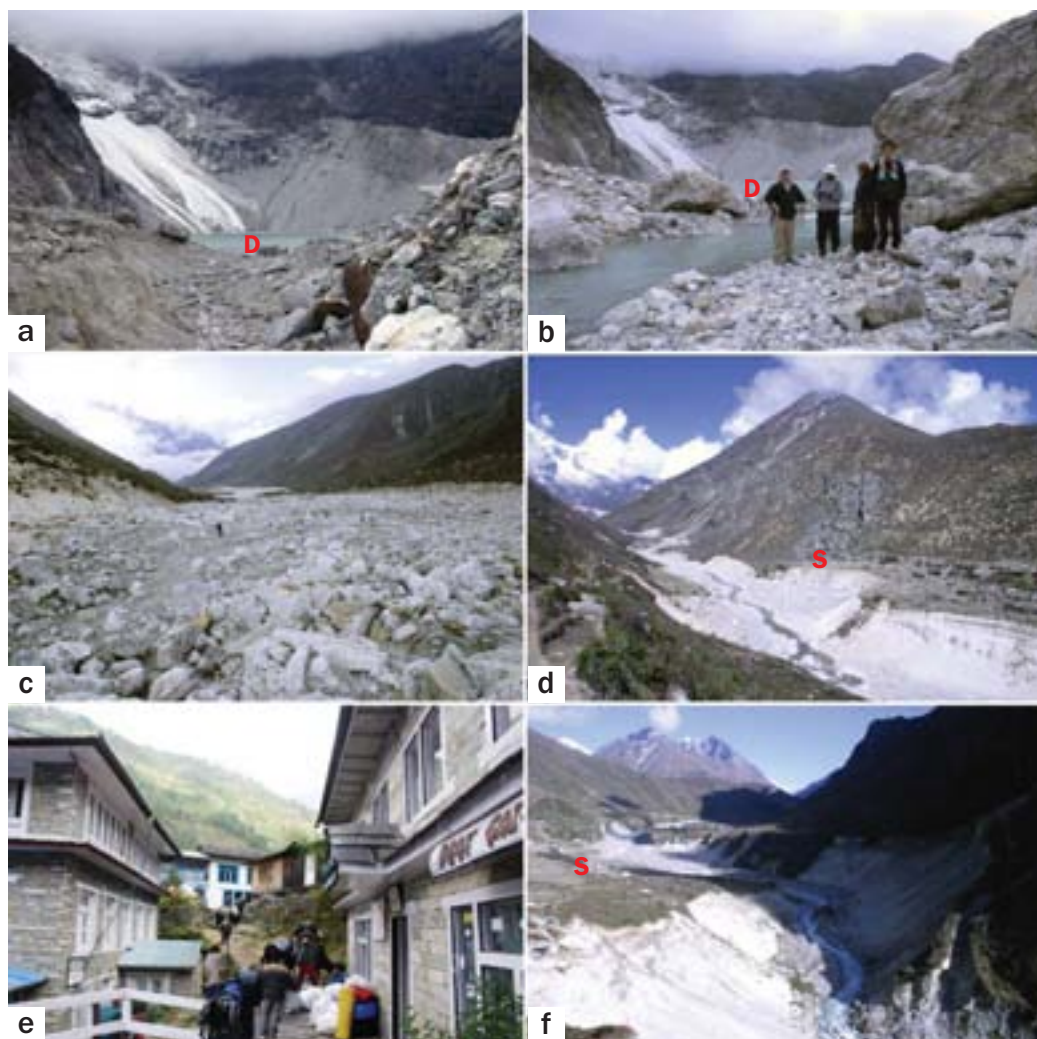
Figure 3.7: Lake Dig Tsho (D) in the Langmoche valley and settlements (S): a) Hanging Langmoche Glacier, Dig Tsho, and outlet of the lake after 1985 GLOF; b) Gentle gradient of the lake outlet through the debris; c) Wide valley downstream; d) Nearest settlement (about 3 km downstream) in the Langmoche valley; e) Phakding village situated on the lowest terrace of the Dudh Koshi River; f) Erosion from 1985 Dig Tsho GLOF at Thamo Teng village

Lake Imja Tsho

Most of the supraglacial lakes formed in the 1960s have now become moraine-dammed lakes due to glacier retreat. The Imja glacial lake is an example of one such lake and has been identified as one of the potentially more dangerous lakes in the Nepal Himalaya. The lake is formed within moraines on all sides and is rapidly extending towards the glacier snout. The end moraine of Lake Imja Tsho is 600m wide. It has an extensive dead ice core, which is often exposed, particularly near the outlet (Figure 3.8). Watanabe et al. (1994 and 1995) reported rapid melting of the debris-covered ice and significant changes in its outlet position.

The catchment of Lake Imja Tsho occupies the northeastern part of the Dudh Koshi sub-basin. The lake itself is located at the toe of its parent glaciers (Imja and Lhotse Shar at 27°59'17" N latitude and 86°55'31" E longitude; Figure 3.9). The Lhotse Shar glacier flows in a south-westerly direction; its highest altitude is 7590m (Peak 38). The Imja glacier is oriented in a north-westerly direction and its highest altitude is 7168m (Peak Baruntse); the terminus of the Imja glacier itself is at about 5100m. These two glaciers coalesce approximately 3.5 km above the terminus and flow westwards just beneath the trekking path to Peak Imjatse (Island Peak 5173m). The Amphu Lapcha glacier, which flows in a northerly direction, is also in the vicinity and falls within the catchment of Imja Lake; however, it is not in direct contact with the lake itself.
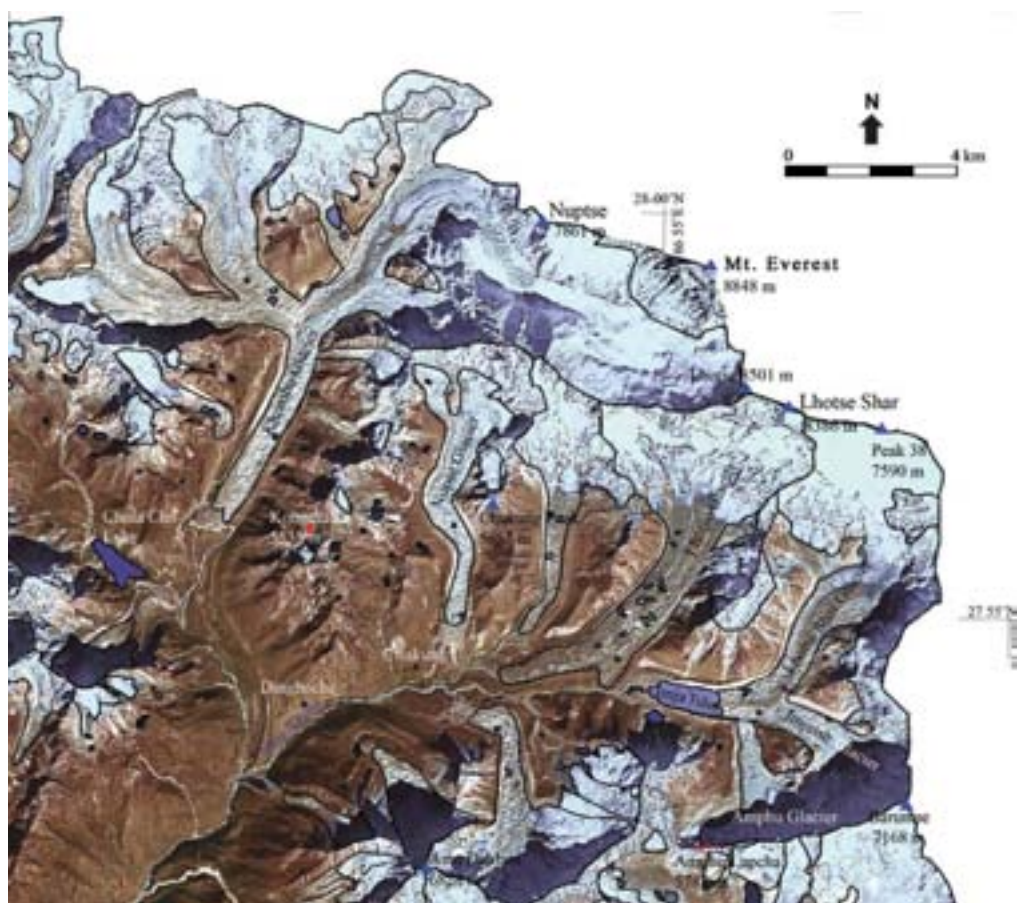

Figure 3.8: Lake Imja Tsho and surrounding glaciers, base image IKONOS

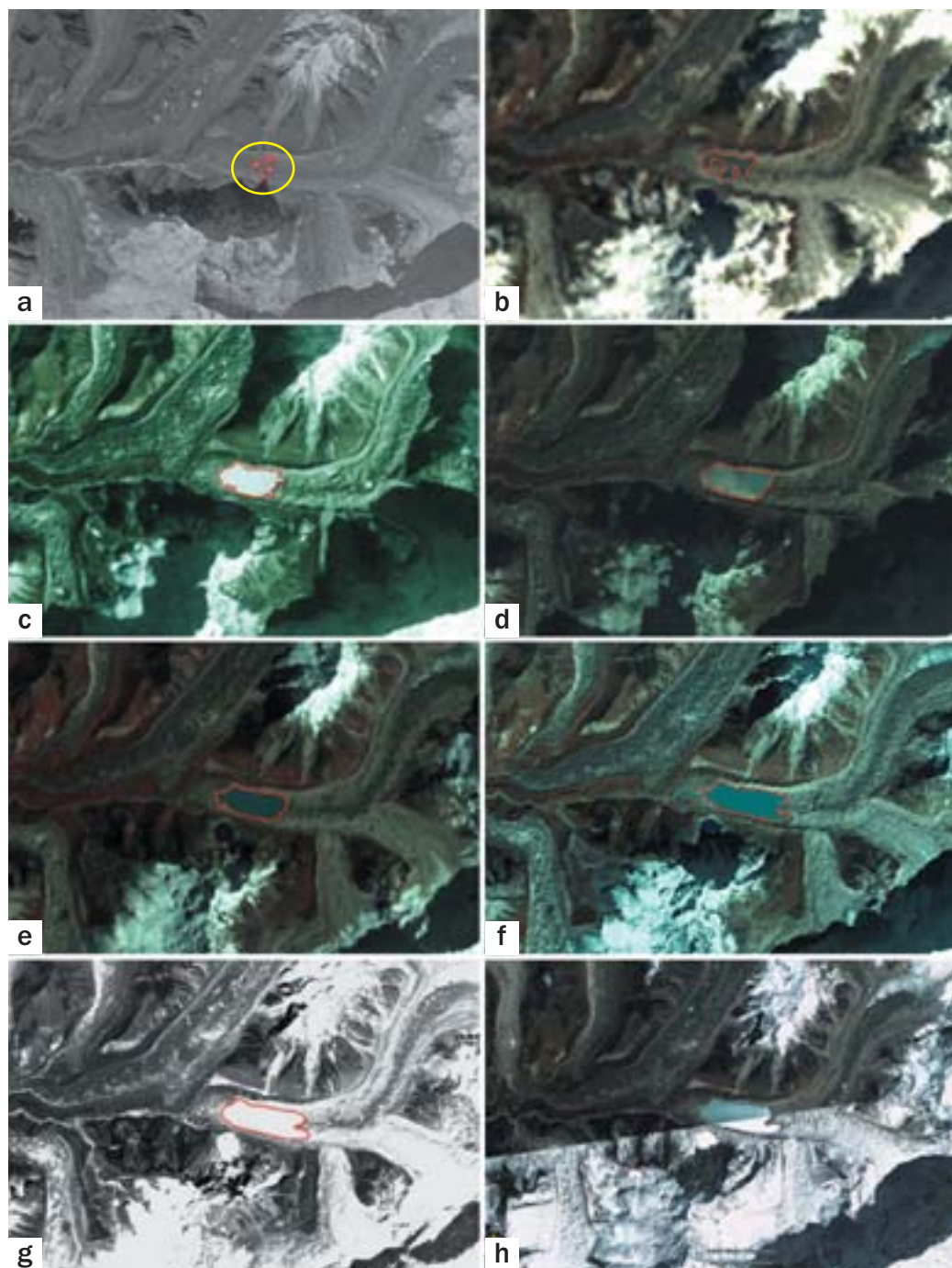Impact of Climate Change on Himalayan Glaciers and Glacial Lakes

Figure 3.9: Satellite images taken on different dates showing the size of Lake Imja Tsho, see Table 3.6 for details: a) Corona (15 Dec 1962); b) Landsat MSS (15 Oct 1975); c) Sp. Shuttle (02 Dec 1983); d) Landsat5 TM (11 Dec 1989); e) Landsat5 TM (22 Sep 1992); f) Landsat 7 etm+ (30 Oct 2000); g) LISS 3 (19 March 2001); h) Google Earth (Jan 2006)

This lake has a history of rapid growth. Unlike Lake Dig Tsho, as shown in the Corona image of 1960 Lake Imja Tsho did not exist in the early 1960's when the area showed only a few small supraglacial ponds (Figure 3.10). The lake began growing in earnest after reaching an area of 0.3 sq.km in 1975; since then its growth has been quite rapid and it attained areas of 0.56, 0.63 and 0.77 sq.km in 1983, 1989 and 2000 respectively. The lake area was 0.83 sq.km from the field survey in 2001 (Yamada 2003) and 0.86 sq.km in 2002 (GEN and CREH 2006). As the area increased, the average depth of the lake diminished from 47m in 1992 (Yamada 1998) to 41.6m in 2002 (GEN 2006) (note that this same study reported a maximum depth of 90.5m in 2002). The volume of water stored in the lake was estimated at 28 million cubic metres in 1992 and 35.8 million cubic metres in 2002. The lake was formed by damming of the debris-covered ice core; hence continuous expansion of the lake is anticipated due to melting of the ice core as a result of global warming. The thickness of the ice core is about 150m near the glacier snout and disappears at the edge of the end moraine (GEN and CREH 2006).
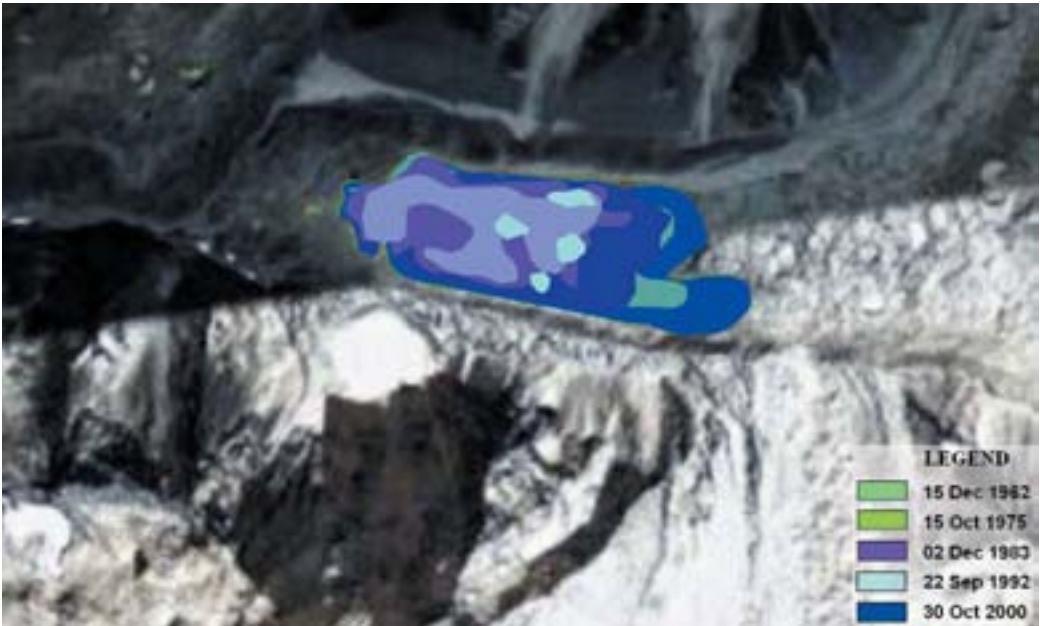

LEGEND
15 Dec 1962
15 Oct 1975
02 Dec 1983
22 Sep 1992
30 Oct 2000

Figure 3.10: Development of Lake Imja Tsho from 1962 to 2006, base image IKONOS

A temporal series of satellite images (from 1962 to 2006) and field verification data show the expansion of the lake from 1962 (Figure 3.10). The lake expanded at an average rate of 42m per year between 1962 and 2001; from 2001 onwards, the rate of change increased to about 74m per year (Table 3.6). The lake has increased in area from 0.82 sq.km in 2001 to 0.94 sq.km in 2006 and in length from 1647 to 2017m during the same period. A recent field visit in October 2006 revealed extensive calving of the glacier snout. Field photographs show exposed ice cliffs in the glacier snout and many large icebergs on the lake (Figure 3.11). Since Lake Imja Tsho is growing so quickly, mitigation measures to reduce the GLOF risks are urgent.

The water draining from the lake through its natural outlet, which runs over the end moraine, is known as the Imja Khola. This river is an important tributary of the Dudh Koshi River, which eventually merges with the Bhote Koshi River below Namche Bazar. Rivers mostly flow through narrow sections with many settlements on the lower and upper terraces (Figure 3.12).
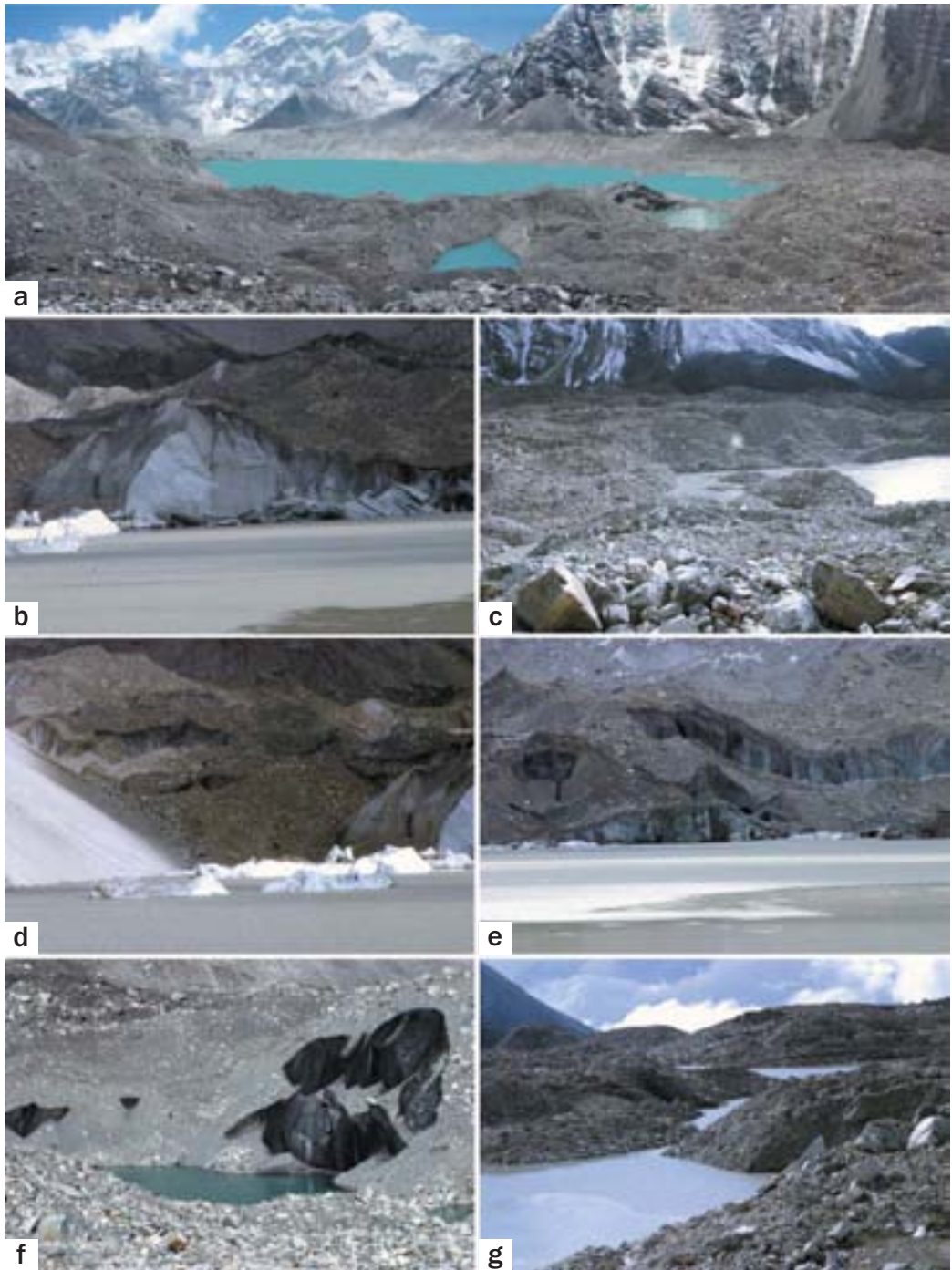
Figure 3.11: Lake Imja Tsho and surrounding environment (Photo: 15 Oct 2006): a) Panoramic view of Lake Imja Tsho; b) Ice cliff at the snout of Imja Glacier; c) Hummocky pattern of moraine indicating dead ice underneath; d) Ice scarps at the glacier snout and icebergs on lake; e) Ice cliff at the terminal moraine; f) Dead ice and a small supraglacial pond; g) Many connected supraglacial ponds
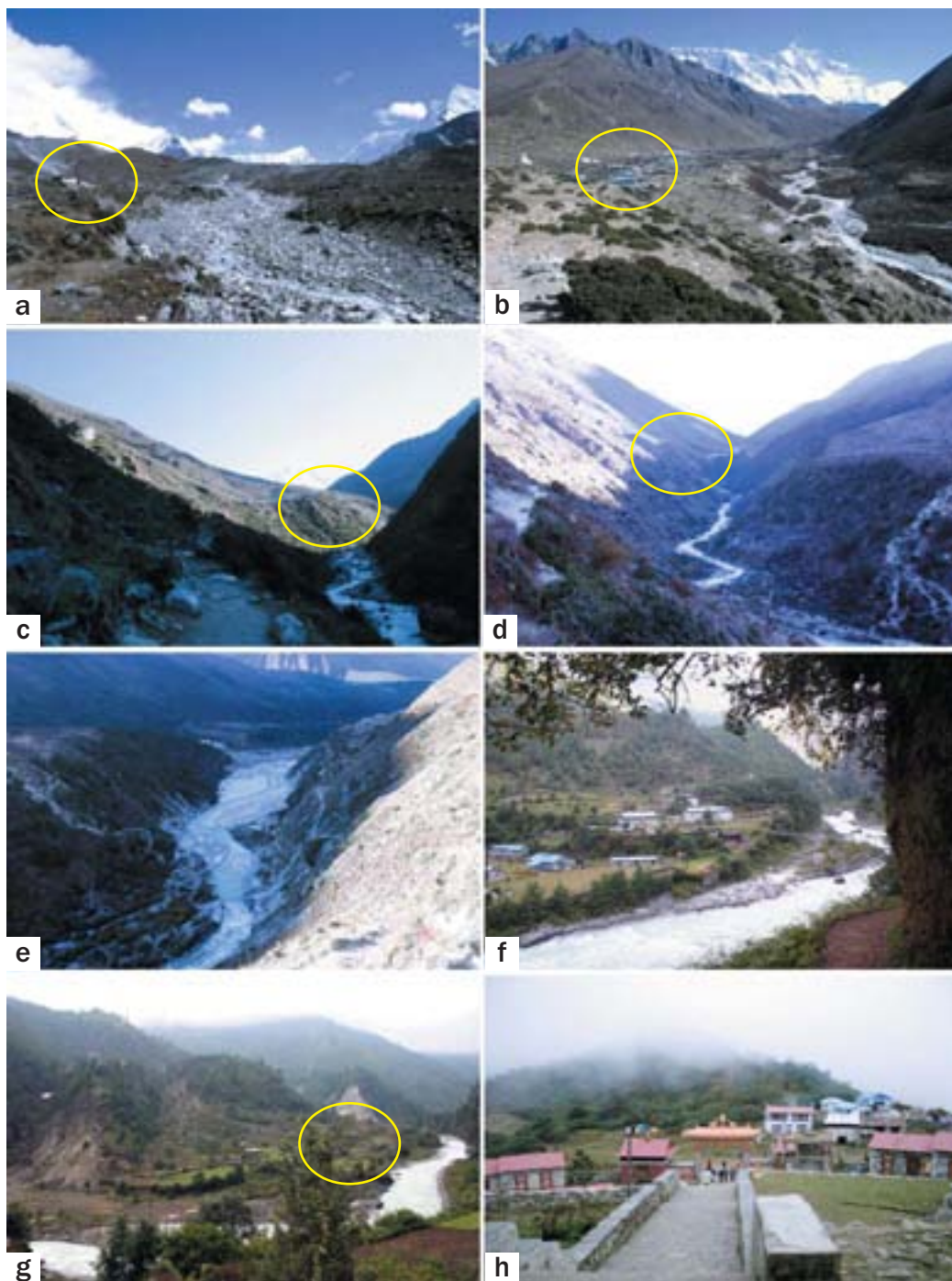
Figure 3.12: Downstream villages of Lake Imja Tsho: a) Chhukung village adjacent to Lake Imja Tsho;
b) Dingboche village (7.5 km from Imja); c) Syomare village; d) Pangboche village (13.6 km from Imja);
e) Pangboche village (close up view); f) Thulo Gumela village near Phakding village; g) Chutawa village;
h) Tengboche village

Table 3.6: Increase in size of Lake Imja Tsho as observed from satellite images of various years

Satellite type and year	Area (sq m)	Area difference (sq m)	Length (m)	Length difference (m)	Total length difference (m)	Average growth rate (m/year)
Corona 1962	27,916		55			
Landsat MSS 1975	309,573	281,657	619	564		
Space Shuttle 1983	568,824	259,251	1137	518		
Landsat5 TM 1989	633,214	64,390	1266	129	1592*	42*
Landsat5 TM 1992	635,945	2,731	1271	5		
Landsat7 etm+ 2000	775,065	139,120	1550	279		
LISS3 2001	823,553	48,488	1647	97		
Google Earth 2006	940,722	117,169	2017	370	467**	74**

Note: *between 1962 and 2001, ** between 2001 and 2006

Glacial lakes in the Pho Chu sub-basin of Bhutan*

Pho Chu is a sub-basin of the Puna Tsang Chu basin and one of the largest sub-basins in Bhutan. (Other sub-basins in the Puna Tsang Chu basin include the Sunkosh, the Dang Chu and the Mo Chu, the Dang Chu being devoid of glaciers.) Mool et al. (2001b) mapped 549 lakes in the Pho Chu sub-basin from topographic maps of the 1960s in the Bhutan Himalaya. Some satellite images (LandSat TM) of a much later period were also used where maps were not available or were of poor quality. The present study was carried out using the NaturalVue of EarthSat satellite images of 2000 and 2001. Comparison of the data shows that over time some new lakes have formed and some previously existing lakes have disappeared. New lakes were identified from the satellite images; similarly, satellite images helped verify that some previously identified lakes, especially supraglacial ones, have now disappeared.

Figure 3.13 shows the distribution of glacial lakes in the Pho Chu sub-basin. In the 1960s, lakes covered an area of 23.49 sq.km; by 2001 the overall area covered by lakes in this sub basin increased to about 25.45 sq.km (Figure 3.13), growth of about 8 per cent. Over the 40 years, a total of 175 lakes have either dried up or become so small that they cannot be mapped. Some 82 new lakes have been formed and are numbered serially from pho_gl_550 to pho_gl_631.

Most of the glacial lakes formed at glacier tongues are increasing in size. Examples of some major lakes are given in the Table 3.7. Among these nine glacial lakes, Pho_gl 209 (Lake

Table 3.7: Area change of major glacial lakes in Pho Chu sub-basin (2001-2006)

Lake ID	Area in 2001 (m²)	Area in 2006 (m²)	Area change %	Remarks
Pho_gl_84	214,078	743,187	247.2	Increased
Pho_gl_148	454,510	635,180	39.7	Increased
Pho_gl_163	369,572	241,808	34.5	Decreased
Pho_gl_164 (Tarina Tso)	280,550	439,103	56.5	Increased
Pho_gl_172	33,522	38,139	13.7	Increased
Pho_gl_206	44,194	0		Vanished
Pho_gl_207	15,463	0		Vanished
Pho_gl_209 (Raphstreng Tso)	145,949	1,240,131	749.7	Greatly increased
Pho_gl_210 (Luggye Tso)	769,800	1086411	41.1	Increased

*Contributed by D.R. Gurung and Karma Toeb

Figure 3.13: Distribution of glacial lakes in the Pho Chu sub-basin, Bhutan

Raphstreng Tso) and Pho_gl 84 have grown in area by about 750 and 250 per cent respectively, whereas two supraglacial lakes from the Bechung glacier have disappeared from the satellite images of 2000–2001.

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Lakes Luggye Tso, Raphstreng Tso, Thorthormi Tso and Tarina Tso

The partial breaching of Lake Luggye Tso in 1994 caused a catastrophic GLOF, the memory of which is still fresh in the minds of people who witnessed it. This GLOF will in all likelihood go down in the history of floods in Bhutan as the most catastrophic event ever recorded both in terms of its magnitude and in terms of the damage it wreaked on the lives, property, and infrastructure of the people downstream. The severity of this event prompted the Department of Geology and Mines (under the Ministry of Trade and Industry, Royal Government of Bhutan), to initiate a number of research activities on the glaciers and glacial lakes in the country.

Numerous studies were conducted on glacial lakes in Bhutan as part of joint Japan-Bhutan, India-Bhutan, and Austria-Bhutan projects from 1995–2004. These studies led to many scientific articles highlighting the risks associated with the lakes, discussing the mechanisms of lake expansion, and assessing the stability of the lakes. Previous sections cited some of these. This section presents different scenarios regarding lake expansion and draws both from earlier work by different experts and from the results of the present work. The discussions focus mainly on the lakes in the Pho Chu basin.

The first detailed work on the expansion of glacial lakes in the Bhutan Himalaya was a time-series of sketches of the major glacial lakes in the Lunana region by Ageta et al. (2000). His subsequent study discussed the evolution of these lakes in detail using maps, photographs, and satellite images. Ageta also studied and discussed the risk that possible outbursts pose on the geophysical environment in and around the lakes.

Luggye Tso

Lake Luggye Tso (Pho_gl 210) is an end moraine-dammed lake in the Pho Chu basin of the Lunana region (Figure 3.14). As late as the 1950s, there were no indications of any lakes being associated with Luggye glacier. The first lake appeared only in 1967 (Gansser 1970) as a supraglacial lake and was measured to be 0.02 sq.km in 1968. Figure 3.15 shows the lake's development from 1967 to 1994. The depth of Luggye Lake was measured in 2000 and shown to be 142m. This glacial lake suffered an outburst event on 7th October 1994. The GLOF from Lake Luggye Tso caused much damage to the downstream valley, including the religiously important Punakha Dzong. After the breach, the lake continued to grow towards the glacier snout and the glacier continued to retreat; in 2001 the lake area measured 1.12 sq.km (Table 3.8). The exposure of ice cliffs on the glacier snout show calving, which contributes to the expansion of the lake towards the glacier (Figure 3.16). The outlet channel is at the same level as the lake surface and has a gentle slope. Evidenced by its bumpy topography, this terminal moraine has an ice core. Both the continuous sliding of the left lateral moraine at the outlet and the presence of an ice core contribute to the possibility of blocking of the previously breached outlet so that the lake could at some time in the future suffer another GLOF event (Figure 3.17).

If the outlet of Lake Luggye Tso is blocked by landslides from the left lateral moraine it will cause the water level of the lake to rise, risking a GLOF event (Figure 3.17) with serious consequences for the Thorthormi lakes further downstream, especially since the Thorthormi glacier has already weakened the left lateral moraine (Ageta et al 2000). Austrian experts Leber and Hausler (2002) concur about the risk from Lake Luggye Tso. In fact, of the possible scenarios that this group examined during their risk assessment of the Luggye GLOF, the

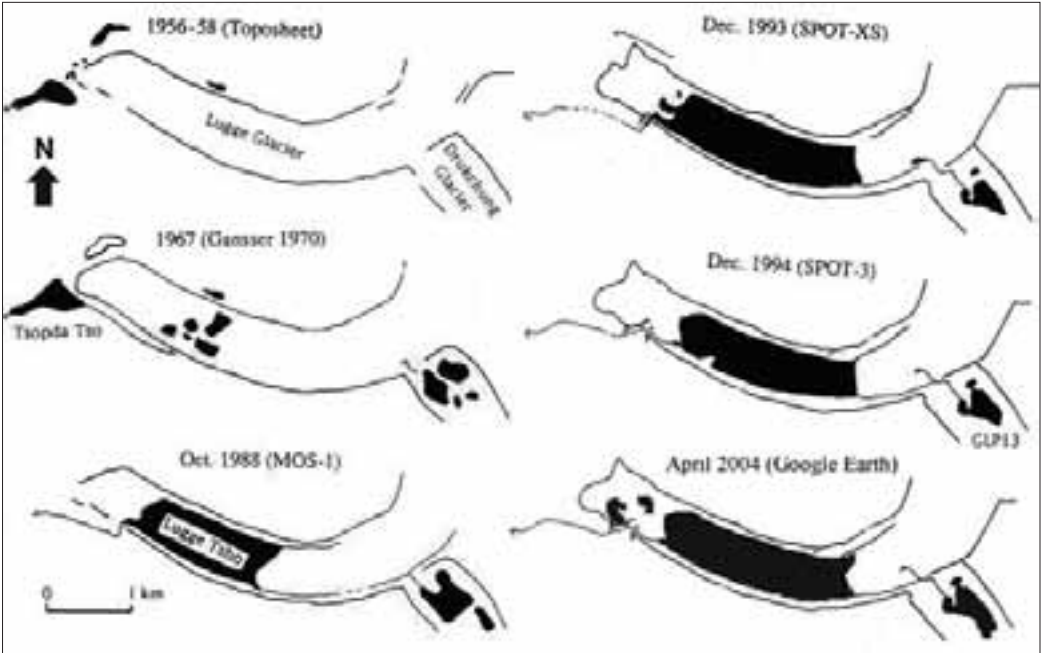**Figure 3.14:** Panoramic view of Lake Luggye Tso and Peak Jamlhari in the background

Figure 3.15: Expansion of Lake Luggye Tso (1956-2004) (modified from Ageta et al. 2000)

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Figure 3.16: Ice cliff of Luggye glacier snout in contact with Lake Luggye Tso

Figure 3.17: The outlet of Lake Luggye Tso through the end moraine

blockage of the outlet by a landslide from the left lateral moraine was considered the "major risk" (Leber and Hausler 2002). This group recommended that the active sliding zone on the left lateral moraine be stabilised at the outlet to allow free flow of water from the lake. In contrast, Dorji (1996) observed no immediate GLOF risk from this lake because of its wide outlet channel. He commented that the risk of flood from this lake is not imminent as the outlet channel is wide enough to discharge any amount of water that will accumulate.

Raphstreng Tso

Lake Raphstreng Tso (Pho_gl 209) lies at an altitude of 4360m. This lake appeared as a supraglacial lake in a 1958 topographic map; topographic maps from 1960 showed that the lake's area was 0.15 sq.km. In 1986 it was 1.65 km long, 0.96 km wide, and 80m deep (Sharma et. al. 1986). Nine years later, the Indo-Bhutan Expedition of 1995 measured a maximum length of 1.94 km, width of 1.13 km, and depth of 107m (Figures 3.18 and 3.19) (Ageta et al 2000). The depth measured in 1999 was about 100m. Some researchers believe that the lake's present dimensions represent its maximum since the upstream section has already reached the bedrock wall. However, field photographs show that the glacier snout is undergoing extensive calving and that the lake can still expand a few hundred more metres (Figures 3.20 to 3.23).

Prior to the 1994 flood from Lake Luggye Tso, the left lateral moraine was 295 to 410m wide (Bhargava 1995). Toe erosion of the moraine initiated by the flood has reduced the width to 178m. This weakening of the lake barrier and the large size of the lake caused grave concern to the Government of Bhutan. An immediate investigation of the stability of the lake was undertaken in 1995. Three phases of mitigation work were carried out on this lake from 1996 to 1998 in an attempt to lower the water level by about 4m. A channel of 78.5m in length and 36m wide at the outlet was manually widened and deepened at the lake outlet. Nevertheless, the risk of a GLOF cannot be ruled out because a large volume of water is still stored in the lake and a chain effect of GLOFs from other adjacent lakes could occur. An additional threat to the stability of Lake Raphstreng Tso comes from hydrostatic pressure exerted by the

Figure 3.18: Lake Raphstreng Tso in contact with the glacier snout and outlet canal

Thorthormi lakes, from which Lake Raphstreng Tso is separated by only a moraine wall. Similar high risk scenarios have also been reported by Dorji (1996) and Leber et al. (2002).
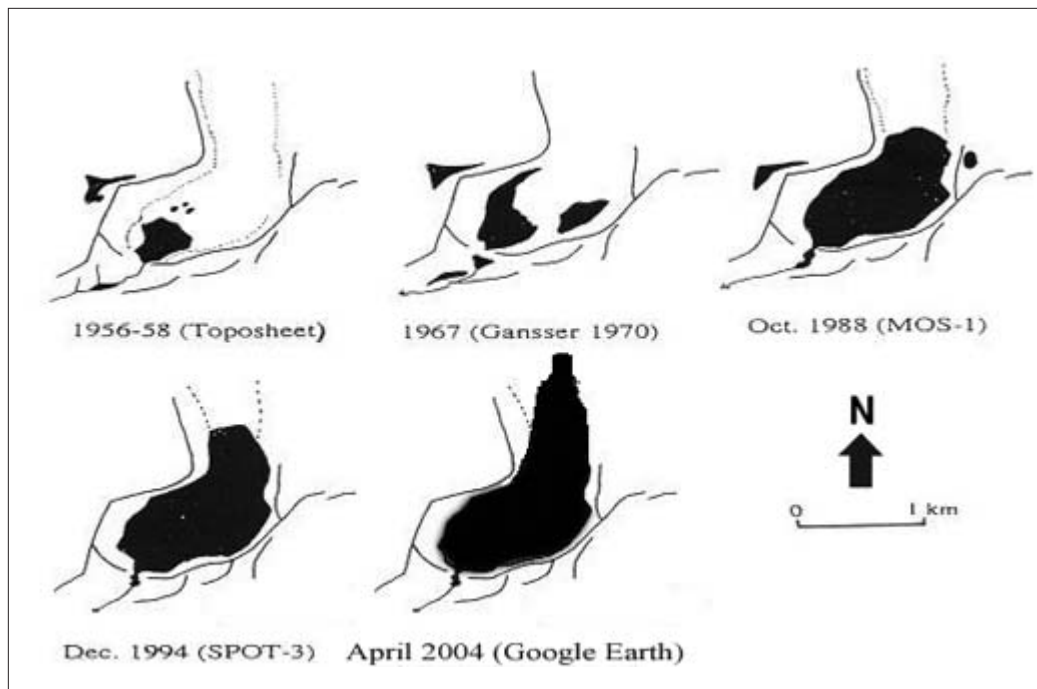

Figure 3.19: Expansion of Lake Raphstreng Tso (1956-2004) (modified from Ageta et al. 2000)

Figure 3.20: Calving of the Raphstreng glacier snout with the expansion of the lake in 2001

Figure 3.21: Raphstreng glacier snout undergoing active calving

Figure 3.22: Lake Raphstreng Tso with newly formed supraglacial ponds on right lateral moraine.

Figure 3.23: Lake Raphstreng Tso with glacier snout. The ripples on the water surface generated by falling ice blocks indicate the active calving of the glacier snout.

Thorthormi lakes

The Thorthormi lakes do not appear in the 1960s maps of the Thorthormi glacier. These supraglacial lakes began to appear on the maps only after 1967. After 1993, many supraglacial lakes became visible, and currently this large glacier contains many supraglacial lakes many of which are merging and growing. The largest of the lakes is Lake Thorthormi Tso. While it does not appear on the 1958 topographic map, some supraglacial lakes are visible on the map reported later by Gansser (Figure 3.24). The Thorthormi terminal moraine (with a width of 30m at its crest) acts as a dam between Lake Thorthormi Tso and Lake Raphstreng Tso. Lake Thorthormi Tso is a supraglacial lake that is 65m higher than Lake Raphstreng Tso and lies directly above it. It is separated from the Pho Chu by a thin, continuously eroding, left lateral moraine. Since Lake Thorthormi Tso is at a higher elevation than Lake Raphstreng Tso, and since the terminal and left lateral moraine are narrow and unstable, this lake and glacier need to be continuously monitored.

Figure 3.24 shows a time series expansion of the Thorthormi lakes from 1956 to 1993. Ageta et al (2000) reported supraglacial lakes on this huge debris-cover glacier in the 1990s. The continuing expansion of these supraglacial lakes was observed in 1998 during the first joint Japan-Bhutan field expedition. This growing lake has a potential for an outburst in the near future for several reasons (Figures 3.25 to 3.28). First, accelerated melting of the ice has been observed; second, there is only a gentle gradient at the snout region; third, the left lateral moraine ridge is being eroded by discharge water from the upstream Luggye Lake; finally, considerable seepage is seen from the left lateral moraine.

Dorji (1996) recommended continuous monitoring of these growing supraglacial lakes. Brauner et al. (2003) conclude from their four-year investigation in the Lunana area that a severe GLOF threat exists in their estimated worst-case scenario in the near future.
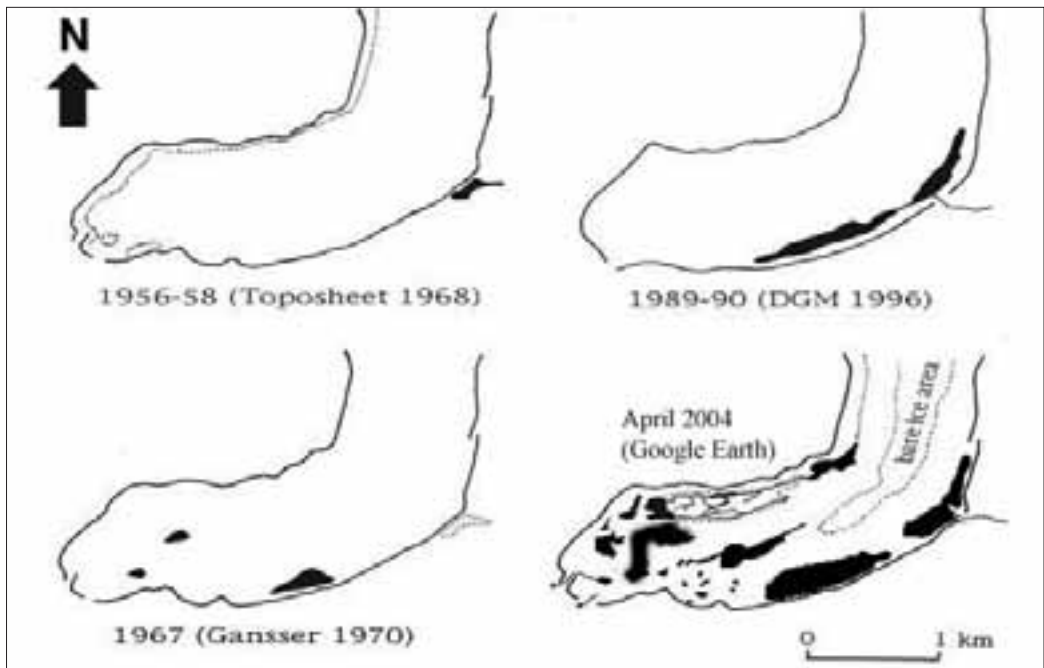
Figure 3.24: Expansion of Lake Thorthormi Tso (1956-2004) (modified from Ageta et al. 2000)

Figure 3.25: Supraglacial lakes formed in the Thorthormi glacier

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Figure 3.26: A glacial lake located in the Thorthormi glacier, near the inlet of Lake Luggye Tso

Figure 3.27: A supraglacial lake at the lower left side of the Thorthormi glacier

Figure 3.28: An avalanche at the accumulation zone of the Thorthormi glacier.

Comparison of changes in the three major lakes

The present work attempted to demarcate changes on the glacial lakes in the Lunana area on a decadal basis from 1968 to 2001 in terms of both area and length. The work was based on the 1950s topographic map and different satellite images such as the Landsat_2 (MSS) of 1978, MOS 1 of 1988, Landsat (TM) of 1998, and NaturalVue for 2001 (Figure 2.8). The results are tabulated in Table 3.8 and are shown graphically in Figure 2.9.

As Figure 2.9 indicates, all three major lakes (Raphstreng, Thorthormi, and Luggye) share a common feature – a sudden increase in area at one point of their evolution. It is clear from the same figure that all the lakes except Raphstreng are still expanding and show similar expansion patterns. Drukchung lake breached in the early 1990s (Leber et al. 2002) and the lake area has remained constant since that time (Figure 2.9).

Table 3.8: **Lake length and area changes in the Lunana region (1968 – 2001)**					
Lake	**Lake area (sq km)**				
	1968	**1978**	**1988**	**1998**	**2001**
Raphstreng	0.16	1.02	1.18	1.23	1.23
Thorthormi	0.02	0.13	0.38	1.20	1.28
Luggye	0.02	0.16	0.84	1.06	1.12
Drukchung	*	0.03	0.15	0.12	0.12
	Lake length (m)				
Raphstreng	579.8	1576.6	1830.5	1931.7	1963.4
Luggye	*	*	1595.4	2169.4	2190.9
* data not available					

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Lake Tarina Tso

Lake Tarina Tso (Pho_gl 164) consists of two lakes – one above the other – at an altitude of 4320m. The lower lake – about 500m long and 300m wide – appears different in size and shape depending on the map. The upper lake clearly shows expansion towards the glacier snout. The outlets of both lakes are clear and drain into the western branch of the Pho Chu. This lake has breached in the past, as evidenced by the breached end moraine, and large debris fan in the downstream area. Although the lake now has a well-defined outlet and is detached from the glacier tongue, its size and the presence of glacial ice on the rocky steep cliff (directly above the lake) are cause for concern.

The second lake lies directly above the lower lake. Shaped like a boomerang, its dimensions are approximately 2 km x 0.3 km, and it is in contact with the glacier tongue resting on a rocky cliff. The outer slope of the end moraine (through which the lake drains) is vegetated and has a gentle slope – there appears to be no immediate danger from this lake.

Lake Tarina Tso (GLP1 as designated by Ageta et al. (2000)) already existed, and was large enough to appear on the 1950 maps (Figure 3.29). GLP1 Lake in 1956/1958 to 1967 gave a clear indication of growing; according to the 1988 maps, however, the lake's shape changed but its size remained more or less constant. The 1989 maps show that the lake had
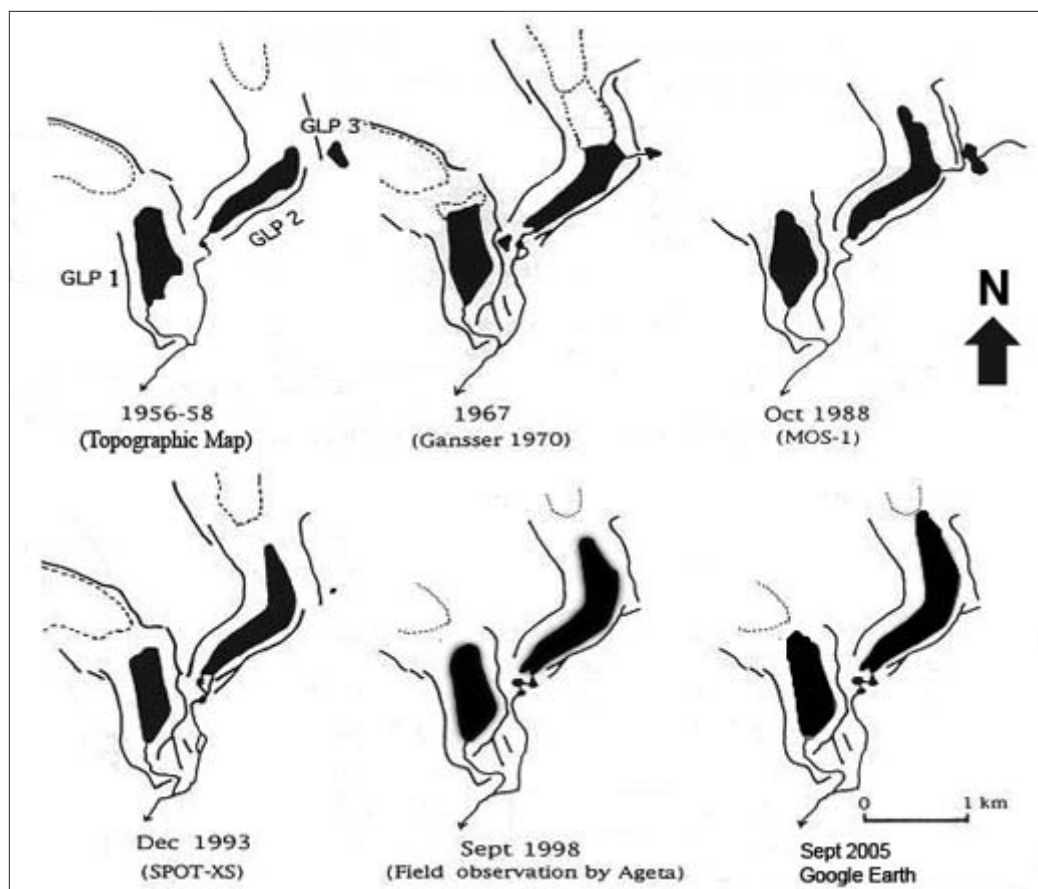

Figure 3.29: Expansion of Lake Tarina Tso (1956-2005) (modified from Ageta et al. 2000)

diminished in size (possibly indicating an outburst event), but in subsequent years the lake is once again expanding. Both lakes have reached their maximum extent, having reached the upstream bedrock wall. A surge wave, resulting from icefall into the lakes, could cause overtopping – the only risk associated with these two lakes (Ageta et al 2000).

Austrian experts made a comprehensive report on the risk assessment of this area. Their assessment of Tarina I (glacial lake point [GLP] 1) states that ice falls from the hanging ice wall could trigger surge waves that might lead to overtopping of Tarina I lake. However, they predict that the impact on the downstream would be low.

As for Tarina II (GLP2), their worst-case scenarios included a chain reaction for a series of events from the glaciers and lakes above this main lake (Figure 3.30). The projected volume of water and sediment it could release to the downstream is estimated to be 3.4 million m^3. However, Dorji (1996) expressed a different opinion and reported that the lakes are safe. In his own words, "Both the lakes in Tarina do not pose any threat of flood".

Figure 3.30: Lakes of Tarina and the surrounding glacial environment

Potentially dangerous glacial lakes in Bhutan

Twenty-four lakes were identified as potentially dangerous based on a set of criteria such as water level rise, the associated mother glacier, and the conditions of the dams and topographical features of the surroundings (Mool et al. 2001).

Considering these criteria, five lakes in the Mo Chu sub-basin, eight lakes in Pho Chu sub-basin, seven lakes in the Mangde Chu sub-basin, three lakes in the Chamkhar Chu sub-basin and one lake in the Kuri Chu sub-basin were identified as potentially dangerous. The present work compares changes in these 24 lakes. Data for the earlier inventory were based on the topographic map of the 1960s and the present data are derived from satellite images (Nature vue of 2000 and 2001). The Thorthormi lakes were not significant in terms of area in the 1960s, and were not considered potentially dangerous at that time. However, since they are expanding at a considerable rate because the associated mother glacier is retreating at a high rate, and since they are sandwiched between two other potentially dangerous lakes

(Lake Raphstreng Tso and Lake Luggye Tso), Thorthormi has been added as number 25 on the list of potentially dangerous lakes. Table 3.9 and Figure 3.31 show the changes that have occurred in these lakes in terms of area, and Table 3.10 and Figure 3.32 show the changes that have taken place in their recorded lengths between the 1960s and 2001.

Of the 24 potentially dangerous lakes identified by Mool et al. (2001), only 15 lakes increased in area while the remaining nine decreased in area between the 1960s and 2001 (Table 3.9 and Figure 3.31). Noteworthy are the lakes associated with the retreating glaciers in the Lunana region that are increasing in area.

Figure 3.32 shows the changes that have taken place in terms of length over the time period. In total 19 lakes increased and five lakes remained unchanged in length.

Lake ID	Area (sq km)		Area change	
	1960s	2000	(sq km)	%
Mo_gl_200	0.05	0.08	0.03	60
Mo_gl_201	0.03	0.06	0.03	100
Mo_gl_202	0.03	0.04	0.01	33
Mo_gl_234	0.23	0.21	-0.02	-8.
Mo_gl_235	0.15	0.12	-0.03	-20
Pho_gl_84	0.21	0.74	0.53	252
Pho_gl_148	0.45	0.63	0.18	40
Pho_gl_163	0.36	0.24	-0.12	-33
Pho_gl_164	0.28	0.43	0.15	53
Pho_gl_209	0.14	1.24	1.1	785
Pho_gl_210	0.76	1.08	0.32	42
Pho_gl_211	0.14	0.11	-0.03	-21
Pho_gl_313	0.02	0.22	0.2	1000
Thorthormi (pho_gl_612 to 621)	Numerous supraglacial ponds on the ablation area of Thorthormi glacier are enlarging and becoming interconnected.			
Mangd_gl_99	0.19	0.2	0.01	5
Mangd_gl_106	0.86	1.11	0.25	29
Mangd_gl_270	0.23	0.25	0.02	8
Mangd_gl_285	0.34	0.35	0.01	2
Mangd_gl_307	0.76	0.84	0.08	10
Mangd_gl_310	0.2	0.19	-0.01	-5
Mangd_gl_385	0.47	0.23	-0.24	-51
Cham_gl_198	0.62	0.59	-0.03	-4
Cham_gl_232	0.2	0.18	-0.02	-10
Cham_gl_383	1.03	1.01	-0.02	-1
Kuri_gl_172	0.1	0.15	0.05	50

Table 3.9: **Area change of potentially dangerous lakes from Bhutan Himalaya (1960-2000)**

Note: the conventional signs in the above table represent negative (-) for decrease in area and positive for increase in area.

	Table 3.10: **Change in length of potentially dangerous lakes in Bhutan**			
Lake ID	**Length in 1960s (km)**	**Length in 2000 (km)**	**Length change**	
			(km)	**(%)**
Mo_gl_200	0.28	0.53	0.25	89
Mo_gl_201	0.32	0.36	0.04	12
Mo_gl_202	0.32	0.32	0	0
Mo_gl_234	0.79	0.79	0	0
Mo_gl_235	0.56	0.58	0.02	3
Pho_gl_84	0.66	1.56	0.9	136
Pho_gl_148	1.28	1.72	0.44	34
Pho_gl_163	1.2	1.2	0	0
Pho_gl_164	1.09	1.8	0.71	65
Pho_gl_209	0.55	1.95	1.4	254
Pho_gl_210	1.98	2.11	0.13	6
Pho_gl_211	0.65	0.66	0.01	1
Pho_gl_313	0.2	0.92	0.72	360
Thorthormi (Pho_gl_612 to621)	Numerous supra glacial ponds on the ablation area of Thorthormi glacier are enlarging and are becoming interconnected.			
Mangd_gl_99	0.6	0.63	0.03	5
Mangd_gl_106	1.48	1.87	0.39	26
Mangd_gl_270	0.85	0.83	-0.02	-2
Mangd_gl_285	0.79	0.96	0.17	21
Mangd_gl_307	1.8	1.93	0.13	7
Mangd_gl_310	0.57	0.64	0.07	12
Mangd_gl_385	0.53	0.86	0.33	62
Cham_gl_198	1.49	1.66	0.17	11
Cham_gl_232	0.56	0.56	0	0
Cham_gl_383	2.64	2.75	0.11	4
Kuri_gl_172	0.85	0.85	0	0

Note: the conventional signs in the above table represents negative (-) for decrease in length and positive for increase in length.
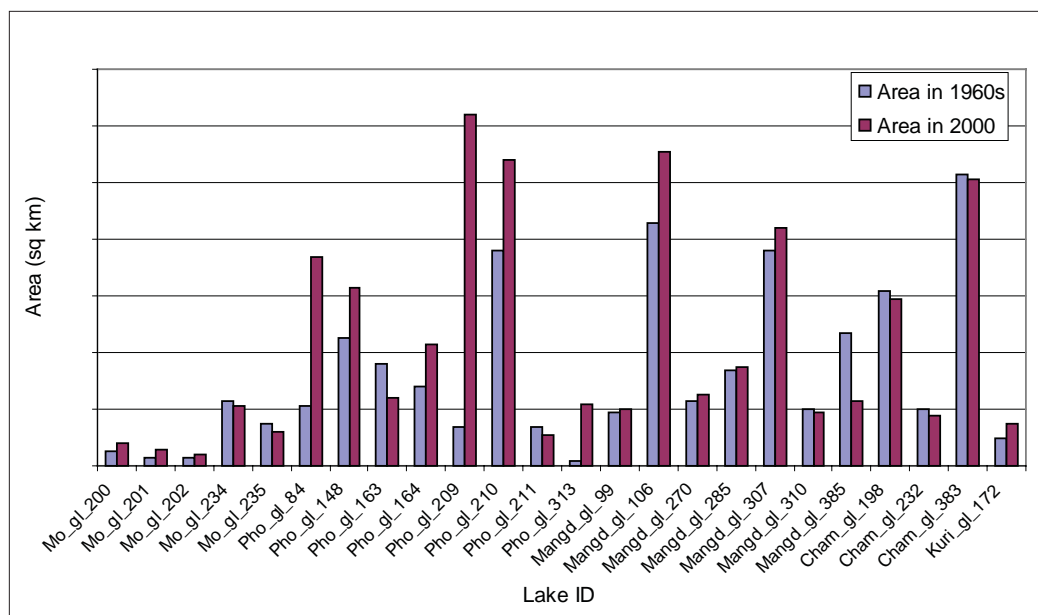
Figure 3.31: Area change of the 24 potentially dangerous lakes in Bhutan from the 1960s to 2001
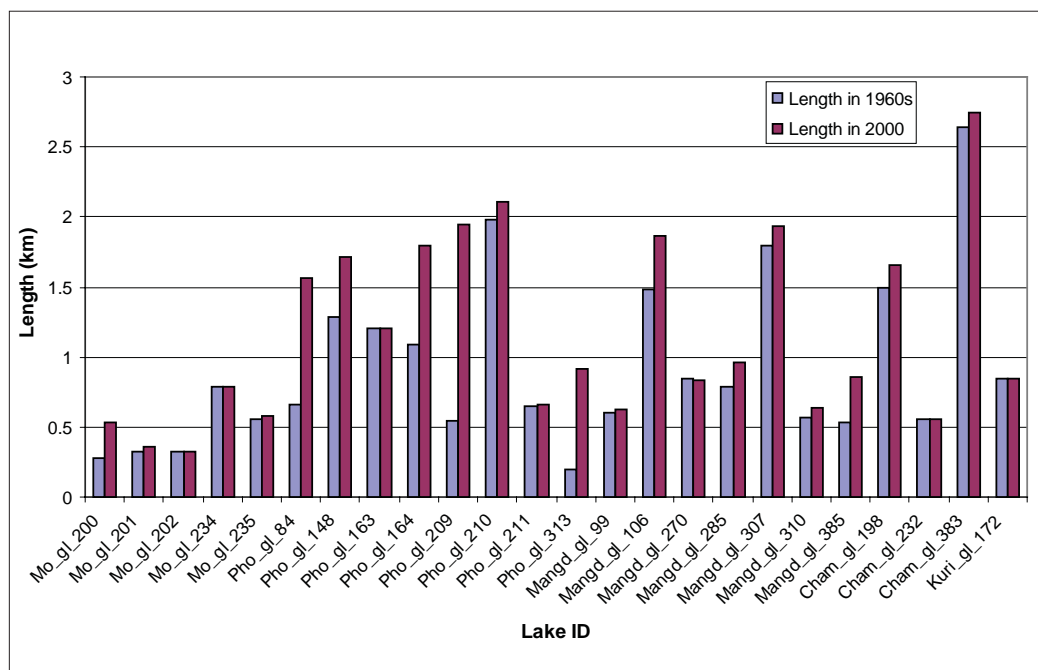

Figure 3.32: Length change of the 24 potentially dangerous lakes in Bhutan from the 1960s to 2001

Comparison of changes in glacial lakes in Bhutan and Nepal

Thirty seven per cent of the lakes which existed in the Dudh Koshi sub-basin of Nepal in the 1960s have now disappeared; similarly 32 per cent of those originally measured in the Pho Chu basin of Bhutan have also disappeared. Most of the lakes that disappeared were either not glacier-fed or were minor supraglacial ponds which merged to form a single large lake. The smaller lakes (less than 2500 sq.m in area) could not be mapped due to the low resolution of the satellite image used in this study as compared to the previous study based on larger scale topographic maps (Mool et al. 2001a, b). Although the number of lakes has decreased, the overall lake area in the sub-basins has increased by 21 per cent in Nepal and 8 per cent in Bhutan. As the area of these lakes – which are associated with glaciers – continues to increase, their downstream areas are at risk for GLOF events. These potentially dangerous lakes as well as their associated glaciers should continue to be monitored.