2 Glacial Lakes in the Hindu Kush-Himalayas

Background

On 11 July, 1981, the diversion weir at the Sunkoshi Hydro-electricity Project, Nepal, was struck by a large flood and incurred significant damage. The flood also destroyed two bridges and extensive sections of the Arniko Highway, resulting in some US $3.0 million in damages (Mool et al. 2001). At the time, the actual cause of the flood was not known. On 4 August, 1985, an outburst flood from Dig Tsho (a glacial lake in the Khumbu Himal, Nepal), totally destroyed the nearly completed Namche Small Hydel Project and caused additional extensive damage farther downstream (Ives 1986; Vuichard and Zimmerman 1987). In the same year, Xu (1988) published a paper that identified the cause of the 1981 flood. He demonstrated that it resulted from the outbreak of the Zhangzangbo (Boqu) glacial lake within China (TAR) that crossed the international border into Nepal.

The combined events prompted the Water and Energy Commission Secretariat (WECS) of Nepal to begin an investigation of the potential threat of glacial lake outburst floods (GLOFs). A substantial body of work was accomplished. The ensuing report (WECS 1987) included the first attempt to inventory glacial lakes in Nepal, to discuss the problems of mitigation, and to explore the possibility of establishing early warning systems in susceptible areas. The WECS investigation was sponsored by the Canadian International Development Agency (CIDA) and ICIMOD. WECS, in collaboration with Lanzhou Institute of Glaciology and Geocryology (LIGG) of the Chinese Academy of Sciences, carried out an inventory based on topographic maps of the 1980s, aerial photographs of 1974 and field investigations of selected glacial lakes of the Pumqu (Arun) and Poiqu (Bhote Koshi-Sunkoshi) river basins in TAR, China in 1987 (LIGG/WECS/NEA 1988).

Mapping of glaciers is also needed in conjunction with the study of glacial lakes. In this context, glacier mapping information is available for the Indian Himalaya as well as for other regions. The Glaciology Division of the Geological Survey of India (GSI) took up systematic glaciological studies in 1974 after its establishment, although conventional studies of a number of isolated Himalayan glaciers had been carried out previously. Beginning with a pilot study of the Baspa basin in the Sutlej catchment by Vohra and Agarwal in 1978, in accordance with the UNESCO (United Nations Educational, Scientific and Cultural Organization) (1970) manual for conducting such inventories, a preliminary survey was undertaken and compiled by V.K. Raina, Geological Survey of India. It covered the upper Indus, Chenab, Ravi, Ganga, and Sutlej basins and was followed by a study of the Jhelum basin of Kashmir, part of the Sutlej basin of Himachal Pradesh, the Bhagirathi basin of Garhwal, the Tista basin of Sikkim and part of the Brahmaputra basin of Arunachal Pradesh. These inventories used the Survey of India topographic maps (scales 1:50,000 or 1:250,000 whichever were available), aided by vertical aerial photographs and satellite imagery (Puri et al. 1999).

The Geological Society of India (2008) published the 'Glacier Atlas of India' in order to provide an accurate and up to date metric plan representation of the existing glacier cover for the Indian part of the Himalayas (Raina and Srivastava 2008). Glacier processes and landforms, including glacial lakes, are mentioned in the report, although no systematic mapping of glacial lakes was undertaken.

China also carried out a country-wide glacier inventory between 1979 and 2002. This was made available in the form of 22 separate documents.

ICIMOD has been involved in glacier and glacial lake inventory and the identification of potentially dangerous glacial lakes since 1986 (e.g., Ives 1986). An initial association with WECS was maintained. WECS evaluated the status of the glacial lakes in Nepal and prioritised individual lakes for further assessment. Field examination of Dig Tsho, Imja Tsho, Tsho Rolpa and the Lower Barun glacial lakes was carried out during 1991-1994 (Mool 1995). WECS extended its exploration with financial assistance from the Japanese International Cooperation Agency (JICA) together with expert advice and direct involvement of several Japanese glaciologists (e.g.,Yamada1998a). Hanisch, together with a team of co-workers, introduced experimental electrical resistivity tomography and low frequency ground penetrating radar in an analysis of the sub-surface conditions of end moraines damming the Thulagi glacial lake in the Manaslu Himal, Nepal (Hanisch et al. 1998) which also contributed to the identification of Thulagi glacial lake as potentially dangerous.

The ICIMOD inventory studies

Between 1999 and 2005, ICIMOD in collaboration with partners in different countries, embarked on the preparation of an inventory of glaciers and glacial lakes, and identification of potential sites for glacial lake outburst floods ('potentially dangerous' glacial lakes), in the Hindu Kush-Himalayan region, using desk-based studies and systematic application of remote sensing. The inventory for Nepal and Bhutan was started in 1999 in cooperation with the United Nations Environment Programme/Regional Resources Centre for Asia and the Pacific (UNEP/RRC-AP), and published in 2001(Mool et al. 2001a and Mool et al. 2001b). Inventories for selected basins in China, India, and Pakistan were started in 2002 with the support of Asia-Pacific Network for Global Change Research (APN), the global change SysTem for Analysis, Research, and Training (START), and UNEP/RRC-AP. Figure 2 shows the approximate geographical area covered by the various studies.

The inventories for Bhutan and Nepal were prepared from analyses of published maps, in most cases from between 1950 and the 1970s, and from analyses of more recent remote sensing images for the other countries. Analysis of the development of lakes was based on a comparison of the remote sensing images and the maps. The individual studies are described in more detail in the following together with selected results from other studies. Details are provided in the individual publications of the studies cited in the following paragraphs. Table 2 summarises the main findings of the studies in Bhutan, China (Ganges sub basins), India, Nepal, and Pakistan.

Figure 2: **Location of regional inventories of glaciers and glacial lakes in Bhutan, China, India, Nepal, and Pakistan prepared by ICIMOD together with national partners (1999-2005) (borders indicative)**

Table 2: **Summary of glaciers, glacial lakes, and lakes identified as potentially dangerous in selected parts of Bhutan, China, India, Nepal and Pakistan** (sources given in the text)

River basin	Glaciers			Glacial lakes		
	Number	Area (sq.km)	Ice reserves (cu.km)	Number	Area (sq.km)	Potentially dangerous
Bhutan						
Amo Chu	0	0	0.00	71	1.83	0
Wang Chu	36	49	3.55	221	6.47	0
Puna Tsang Chu	272	503	43.27	980	35.08	13
Manas Chu	310	377	28.77	1383	55.51	11
Nyere Ama Chu	0	0	0.00	9	0.07	0
Northern basins	59	388	51.72	10	7.81	0
Total	**677**	**1317**	**127.31**	**2674**	**106.77**	**24**
China (Ganges sub basins within China)						
Jiazhagangge	96	143	NA	14	0.52	1
Daoliqu	43	60	"	7	0.38	-
Majiacangbu	147	216	"	69	4.73	11
Jilongcangbu	180	419	"	72	3.32	2
Poiqu	127	231	"	91	15.66	9
Pumqu	716	1408	"	383	52.01	38
Rongxer	205	301	"	183	8.40	16
Zangbuqin	64	86	"	5	0.18	-
Total	**1578**	**2864**	**"**	**824**	**85.19**	**77**
India						
Himachal Pradesh						
Beas	358	758	76.40	59	236.20	5
Ravi	198	235	16.88	17	9.16	1
Chenab	681	1705	187.66	33	3.22	5
Satluj	945	1218	94.45	40	136.46	3
Sub-basins	372	245	11.96	7	0.18	2
Total	**2554**	**4161**	**387.35**	**156**	**385.22**	**16**
Uttaranchal (Uttarakhand)						
Yamuna	124	173	17.88	20	0.17	0
Bhagirathi	393	1034	143.41	32	0.44	0
Alaknanda	540	1675	191.36	54	1.37	0
Kali	382	1178	122.78	21	0.51	0
Total	**1439**	**4060**	**475.43**	**127**	**2.49**	**0**
Tista river basin (Total)	**285**	**577.**	**64.78**	**266**	**20.20**	**14**
Nepal						
Koshi River	779	1410	152.06	1062	25.09	16
Gandaki River	1025	2030	191.39	338	12.50	4
Karnali River	1361	1740	127.81	907	37.67	0
Mahakali River	87	143	10.06	16	0.38	0
Total	**3252**	**5324**[a]	**481.32**	**2323**	**75.64**	**20**
Pakistan (Indus river basin)						
Swat	233	224	12.22	255	15.86	2
Chitral	542	1904	258.82	187	9.36	1
Gilgit	585	968	83.34	614	39.17	8
Hunza	1050	4677	808.79	110	3.21	1
Shigar	194	2240	581.27	54	1.09	0
Shyok	372	3548	891.80	66	2.68	6
Indus	1098	688	46.38	574	26.06	15
Shingo	172	37	1.01	238	11.59	5
Astor	588	607	47.93	126	5.52	9
Jhelum	384	148	6.94	196	11.78	5
Total	**5218**	**15041**	**2738.50**	**2420**	**126.32**	**52**
Grand Total	**15,003**	**33,344**	**NA**	**8,790**	**801.83**	**203**

Note: The Thorthormi lake in Bhutan has also been identified as potentially dangerous (Karma et al. 2008)
[a] Total is higher than addition total as a result of rounding.

Criteria for defining 'potentially dangerous' or critical lakes

A step-by-step approach was taken by ICIMOD during the inventory study to identify potentially dangerous lakes, i.e., critical lakes warranting further investigation. The criteria used to identify these lakes are based on field observations, processes and records of past events, geomorphological and geo-technical characteristics of the lake and surroundings, and other physical conditions. Identification was also based on the condition of lakes, dams, associated glaciers, and topographic features around the lakes and glaciers. The major criteria used were as follows (Mool et al. 2001a; Mool et al. 2001b; Mool and Bajracharya 2003; Bhagat et al. 2004; Sah et al. 2005; Roohi et al. 2005; Wu Lizong et al. 2005):

1. Large lake size and rapid growth in area
2. Increase in lake water level
3. Activity of supra-glacial lakes at different times
4. Position of the lakes in relation to moraines and associated glacier
5. Dam condition
6. Glacier condition
7. Physical conditions of surroundings

Dam condition

a) Narrow crest area
b) No drainage outflow or outlet not well defined
c) Steepness of slope of the moraine walls
d) Existence and stability of ice core and/or permafrost within moraine
e) Height of moraine
f) Mass movement, or potential mass movement, on the inner slope and/or outer slope of moraine
g) Breached and closed in the past and the lake refilled with water
h) Seepage through the moraine walls

Glacier condition

a) Condition of associated glacier
b) Hanging glacier in contact with lake
c) Large glacier area
d) Rapid glacier retreat
e) Debris cover on the lower glacier tongue
f) Gradient of glacier tongue
g) Presence of crevasses and ponds on glacier surface
h) Toppling/collapsing of ice from the glacier front
i) Ice blocks draining to lake

Physical conditions of surroundings

a) Potential rockfall/slide (mass movement) sites around the lake
b) Large snow avalanche sites immediately above the lake
c) Neo-tectonic and earthquake activities around or near the lake
d) Climatic conditions, especially large inter-annual variations
e) Very recent moraines of tributary glaciers that were previously part of a former glacier complex, and with multiple lakes that have developed due to glacier retreat (e.g. Lunana area in Pho Chu basin in Bhutan)
f) Sudden advance of a glacier towards a lower tributary or main glacier which has a well-developed frontal lake

Spot field checking is necessary for glacial lakes that are considered to be at risk of producing outburst floods that could cause loss of life and damage to property in the downstream areas.

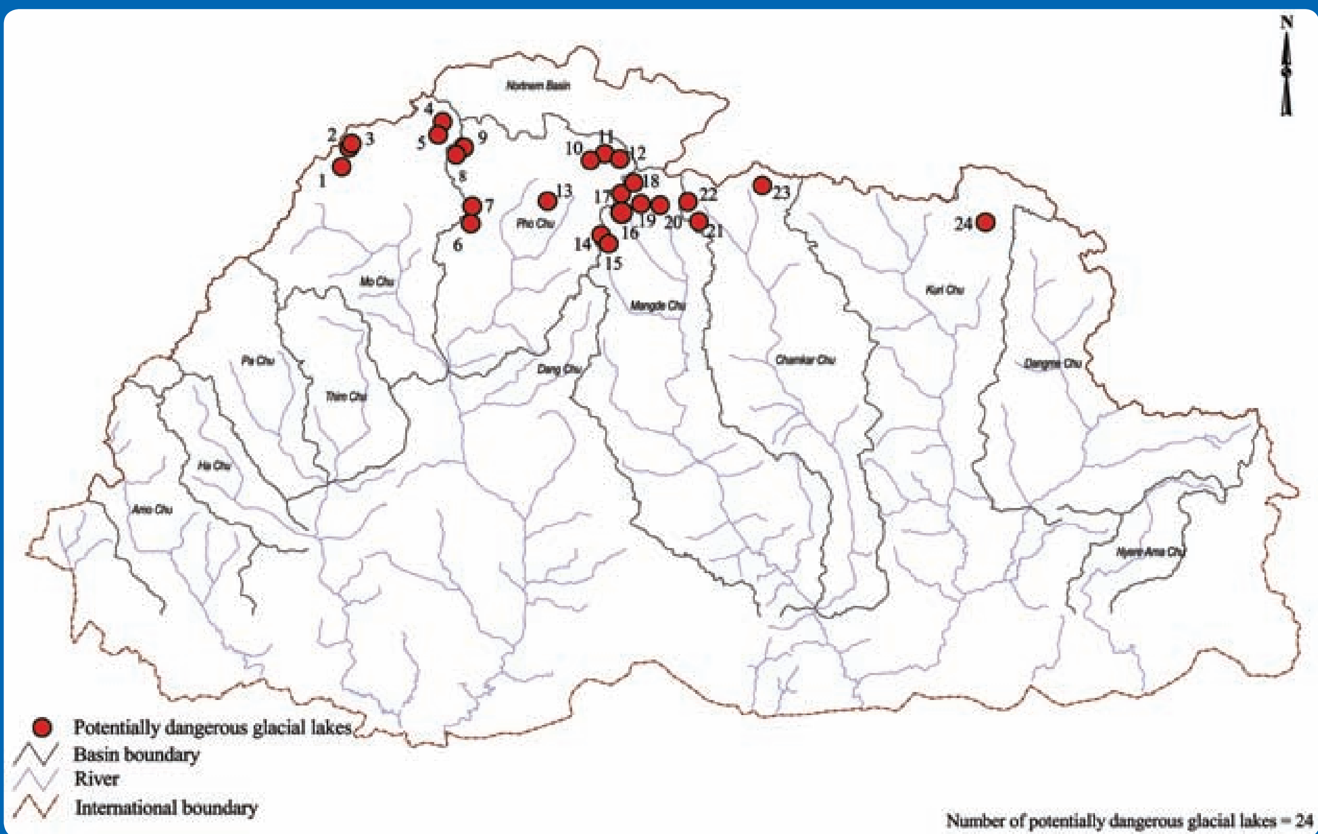
Glacial lakes of Bhutan

The inventory survey in Bhutan was undertaken in 2001 (Mool et al. 2001b). The inventory used the 1:50,000 scale topographical survey maps published between the 1950s and the 1970s by the Survey of India, together with Land Observation Satellite (LANDSAT) Thematic Mapper (TM) images on a scale comparable to the topographical maps. A total of 677 individual glaciers were identified (total area approximately 1,317 sq.km), and 2,674 glacial lakes, of which 24 were classified as potentially dangerous (Table 2 and Annex, Table A1; Figure 3). The great majority of lakes were very small. Glacial lakes with an area of more than 0.02 sq.km and in contact with, or close to, the main glacier, together with other criteria, were analysed to estimate potential risk. Several larger than 1.0 sq.km were immediately classed as potentially dangerous.

Several years prior to the inventory, on 7 October 1994, a glacial lake outburst flood occurred from Luggye Tsho in the watershed 90 kilometres upstream of Punakha Dzong in Bhutan. The resulting deluge along the Pho Chhu River caused extensive material damage and some loss of life. At the time there was little public awareness of the potential dangers from GLOFs. Nevertheless, the Royal Government of Bhutan sent several teams to the area: efforts were made to mitigate the losses and steps were taken to investigate the glaciers and several associated lakes. The level of Raphstreng Tsho was lowered using extensive manual labour, although it was realised that there remained the prospect of subsequent outbursts from the same group of glaciers. Assessment of available documents and news media reports by Watanabe in 1995 added considerably to knowledge about the degree of stability of several of the larger glacial lakes in Bhutan (Watanabe and Rothacher 1996).

Preparation of an updated inventory of major glacial lakes and assessment of glacial lake outburst flood potential in Bhutan, including ranking of potentially unstable glacial lakes, was also undertaken during the Japan-Bhutan Joint Research of 1998. Thirty glacial lakes were recorded and full inventory sheets were prepared. Risk assessments were made for future monitoring (Ageta and Iwata 1999).

Figure 3: **Location of glacial lakes that were considered to be potentially dangerous in Bhutan in the 2001 inventory** (for details of lakes see Annex, Table A1)



Source: Mool et al. (2001)

Based on a study of 66 glaciers from the topographic maps of 1963 and satellite images of 1993, Karma et al. (2003) reported that glacier retreat had averaged 8.1% in the Bhutan Himalaya over this period. In 1963, the area covered by glaciers was 146.9 sq km; by 1993, this had been reduced to 134.9 sq.km. Later, based upon assessment of accelerated ice melt, gentle gradient at the snout region, eroding left lateral moraine ridge by discharge water from Luggye lake further upstream, and many seepages from the left lateral moraine, Karma et al. (2008) concluded that the growing Thorthormi glacial lake had a potential for outburst in the near future. This supplemented the previous work of Gansser (1966), Watanabe and Rothacher (1995), Häusler et al. (2000), and Richardson and Reynolds (2000). At present, there are 25 lakes in Bhutan identified as potentially dangerous and warranting further investigation.

Glacial lakes in the Ganges Basin within China

The present report focuses on the four Himalayan countries of Bhutan, India, Nepal, and Pakistan. However, glacial lake outbursts can have transboundary impacts (Figure 1 and Table 1), thus a brief description of the glacial lakes of the Ganges river basin lying within the Tibet Autonomous Region (TAR) of China is also relevant. An inventory study was conducted by ICIMOD jointly with the Cold and Arid Regions Environmental and Engineering Research Institute/Chinese Academy of Sciences (CAREERI/CAS) and the Bureau of Hydrology Tibet, China, to map the glaciers and glacial lakes in eight sub-basins of the Ganges basin within the Tibet Autonomous Region of the PR China (Daoliqu, Jiazhangangge, Jilongcangbu, Majiacangbu, Poiqu, Pumqu, Rongxer, and Zangbuqin basins). Altogether 824 lakes covering an area of 85.19 sq.km were identified, of which 77 were categorised as potentially dangerous (Table 2) (Wu Lizong et al. 2005).

Glacial lakes of India

Himachal Pradesh

In 2004, the CSK Himachal Pradesh Agricultural University (CSKHPAU) collaborated with ICIMOD to prepare an inventory of glaciers and glacial lakes in the Himachal Pradesh (HP) Himalayas. The study identified 2,554 glaciers with a total area of 4,161 sq.km. Using remote sensing techniques, 156 glacial lakes were identified with a total area of 385 sq.km, of which 16 were considered potentially dangerous (Table 2 and Annex Table A2) (Bhagat et al. 2004).

Uttaranchal (Uttarakhand)

In 2004/05, the Wadia Institute of Himalayan Geology (WIHG) and ICIMOD collaborated to produce an inventory of glaciers and glacial lakes for the State of Uttaranchal (Uttarakhand). The study identified 1,439 glaciers with a total area of 4,060 sq.km, and 127 glacial lakes with a total area of approximately 2.5 sq km. Most were very small and none were identified as potentially dangerous (Table 2) (Sah et al. 2005).

Tista River Basin, Sikkim

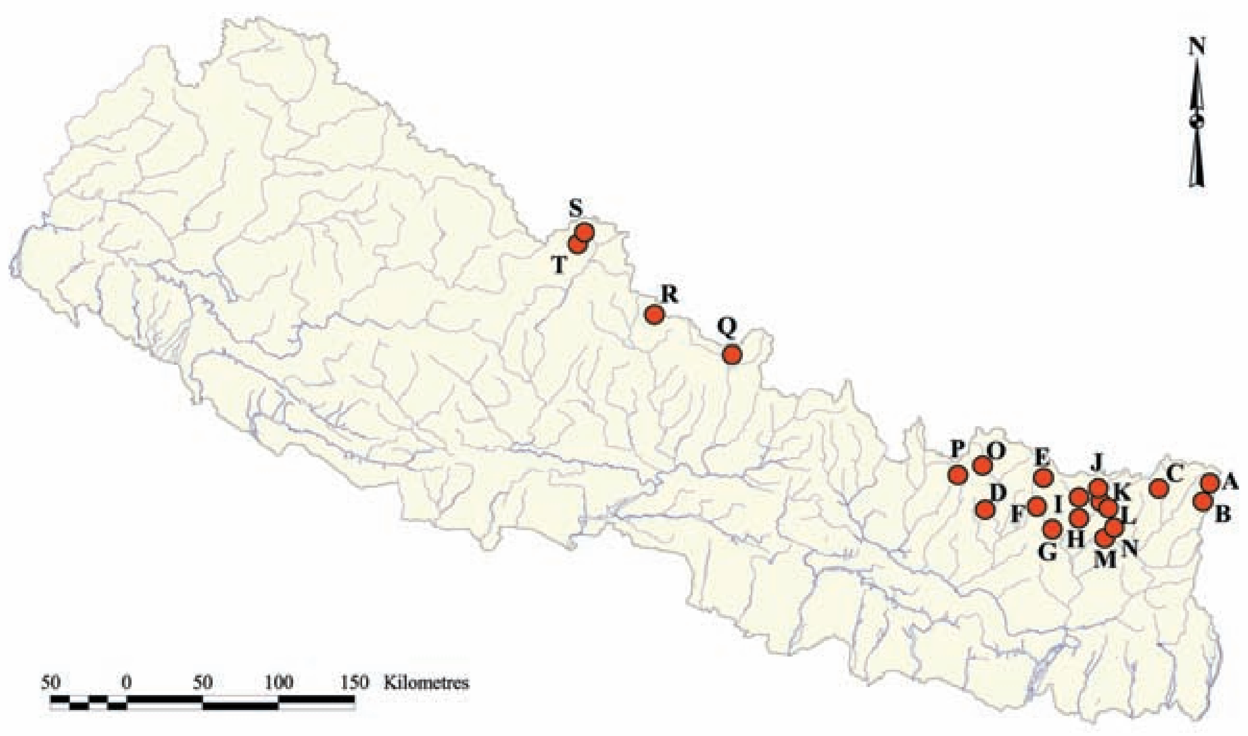
In 2003, ICIMOD, extended the inventory to the Tista river basin in the Sikkim Himalayas, India. This study identified 285 glaciers with a total area of 577 sq.km together and 266 glacial lakes, 14 of which were rated as potentially unstable (Table 2 and Annex, Table A3) (Mool et al. 2003).

Glacial lakes of Nepal

The Nepal inventory was carried out between 1999 and 2001 using topographic maps published by the Survey of India between 1950 and the 1970s (1:63,360) and by the Survey Department, Government of Nepal in 1996 (1:50,000), together with LANDSAT TM, IRS (Indian Remote Sensing)1D LISS3 (Linear Imaging and Self-Scanning Sensor) and some selected SPOT (Système Probatoire d'Observation de la Terre/Satellite Pour l'Observation de la Terre) satellite images from between 1984 and 1994. The inventory identified 3,252 glaciers with a total area of 5,324 sq.km, and 2,323 glacial lakes with a total area of about 76 sq.km (Table 2 and Annex, Table A4; Figure 4) (Mool et al. 2001a). The great majority of the lakes were very small and had probably originated in the recent past. Altogether 20 lakes were recorded as potentially unstable and warranting further investigation, including the Tsho Rolpa, Imja, Thulagi, and Lower Barun lakes.

From 2008 through 2009/10, ICIMOD with the support of the World Bank, Sida and the Norwegian Ministry of Foreign Affairs embarked on a revision of the first inventory in a desk-based study using remote sensing data and other information. The study identified 1,466 glacial lakes in Nepal (down from 2323) with a total area of 65 sq.km (down from 76 sq.km), of which 21 were identified as potentially dangerous. The reduction in the number of lakes appeared mainly to reflect

Figure 4: **Location of glacial lakes reported as being potentially dangerous in Nepal in 2001**



Source: Mool et al. (2001)
A = Nagma Pokhari (Tamor); B = (unnamed) (Tamor); C = Lower Barun (Arun); D = Lumding (Dudh Koshi); E = Imja (Dudh Koshi);
F = Tam Pokhari (Dudh Koshi); G = Dudh Pokhari (Dudh Koshi); H = (unnamed) (Dudh Koshi); I = (unnamed) (Dudh Koshi);
J = Hungu (Dudh Koshi); K = East Hungu 1 (Dudh Koshi); L = East Hungu 2 (Dudh Koshi); M = (unnamed) (Dudh Koshi);
N = West Chamjang (Dudh Koshi);O = Dig Tsho (Dudh Koshi); P = Tsho Rolpa (Tama Koshi); Q = (unnamed) (Budhi Gandaki);
R = Thulagi (Marsyangdi); S = (unnamed) (Kali Gandaki); T = (unnamed) (Kali Gandaki)

merging of small lakes; the average lake area increased. The lakes of potential concern were further grouped into three categories: Category I – requiring detailed field investigation and mapping (6), Category 2 – requiring close monitoring with reconnaissance field surveys (4), and Category 3 requiring periodic observation (11) (Annex, Table A5). Five of the 21 lakes were not listed during the inventory study of 2001 as potentially dangerous, and four of the lakes identified in the original study as potentially dangerous were removed from the list (Annex, Tables A4, A5) (ICIMOD 2009, unpublished).

Glacial lakes of Pakistan

In 2005, the Water Resources Research Institute (WRRI) of the Pakistan Agricultural Research Council (PARC) collaborated with ICIMOD to compile an inventory of glaciers and glacial lakes in the Indus basin in Paksiatn, from a series of studies carried out between 2002 and 2005. The study identified a total of 5,218 glaciers with an area of 15,041 sq.km, and 2,420 glacial lakes, 52 of which were considered potentially dangerous (Table 2 and Annex, Table A6) (Roohi et al. 2005). The upper Indus basin and its tributaries, covering parts of the Karakorum, Hindu Kush, and Himalayas, is estimated, with input from seasonal snowmelt and glacier melt, to provide about half of the entire flow of the Indus River.

Total glaciers and glacial lakes in the Hindu Kush-Himalayan region

The inventory studies in the five Hindu Kush-Himalayan countries of Bhutan, China, India, Nepal, and Pakistan, identified a total of 15,003 glaciers, covering an area of about 33,344 sq.km, and 8,790 glacial lakes, of which 203 were identified as potentially dangerous (Table 2) or 204 with the addition of Thorthormi glacial lake in Bhutan. The inventory still does not cover the Himalayan areas of Arunachal Pradesh and Jammu and Kashmir in India, Afghanistan, or Myanmar; thus the numbers for the whole of the Hindu Kush-Himalayan region will be higher.

Extra-regional involvement

Interest in glacial lakes in the region increased as the potential for serious downstream damage became more widely discussed. Several international agencies continued or expanded their support for the ICIMOD activity (CIDA, JICA, UNEP). At the same time, several institutions and individual university groups from outside the region became involved, or extended earlier investigations in the Nepal and Bhutan Himalaya and northern Pakistan. There has been a heavy focus of interest on the Imja glacier and lake (Imja Tsho) and Tsho Rolpa in Nepal, as well as investigations of glacial lakes in the Bhutan Himalaya (e.g., Watanabe and Rothacher, 1996; Häusler and Leber, 1998). Many non-regional institutions, such as Hokkaido, Nagoya, and Tokyo Universities in Japan, under the Glaciological Expedition to Nepal (GEN) (Yamada 1998a, 1998b), studied glacial lakes in Nepal and Bhutan. The National Data Center for Snow and Ice, University of Colorado/ NASA, USA is archiving data on glaciers under a GLIMS (Global Land Ice Measurements from Space) project. Institutions from the UK, such as Aberystwyth University and Reynolds Geo-Sciences Ltd., and from Germany, studied glacial lakes in Nepal and Bhutan, including Tsho Rolpa (Richardson and Reynolds 2000) and Thulagi (Hanisch et al. 1998). Kennneth Hewitt and his team from the Cold Regions Research Centre, Wilfrid Laurier University, Ontario, Canada, carried out various field investigations in the Karakorum in Pakistan from the 1960s onwards (Hewitt 1982, 2009). The University of Vienna carried out studies of glacial lakes in Bhutan for possible mitigation activities (Häusler and Leber 1998; Häusler et al. 2000). Vrije Universiteit, Amsterdam, carried out an engineering and geomorphological analysis of the moraine dam of Tsho Rolpa glacial lake in the Nepal Himalaya (Modder and Olden 1996).

Other examples include basic studies for assessing the impact of climate warming on the Himalayan cryosphere, with field work in the Nepal Himalaya and on the Tibetan Plateau, conducted between1994 and 1996 by the Institute of Hydrospheric-Atmospheric Sciences, Nagoya University, Japan; the Department of Hydrology and Meteorology, Ministry of Science and Technology, Nepal; and the Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Sciences (Nakawo et al. 1997); a project between 1997 and 1999 to study the rapid shrinkage of summer-accumulation type glaciers in the Nepal and Bhutan Himalaya (Ageta et al. 2001); and a computer-aided study on the rapid shrinkage of glaciers conducted between1998 and 2000 (Naito et al. 2000). Many of the above studies were carried out under 'Cryosphere Research in the Himalayas' (CREH) supported by the Grant in Aid for Scientific Research Programme from the Japanese Ministry of Education, Science, Sports and Culture.