Section 2

Field Investigations and Risk Assessment

End moraine complex of Thulagi glacial lake with unnamed peak in the background, 15 July 2009

6 Field Investigations

Three of the high priority lakes were subjected to intense field investigation. Both the physical conditions and the potential socioeconomic impacts that would result from a possible lake outburst were investigated. This included topographical and bathymetric mapping, hydrometeorological observations, and engineering geological, geophysical, and glaciological research. Potential downstream impacts were estimated using flood-outburst modelling to show which areas would be affected in a worst case situation. This entailed mapping settlements, infrastructure, agricultural land and other features of socioeconomic significance located within the perimeter of the modelled flood limits.

The fieldwork was undertaken between 4 May 2009 and 2 June 2009 for Imja Tsho, 6 July 2009 and 3 August 2009 for Thulagi Lake, and 24 August 2009 and 18 September 2009 for Tsho Rolpa.

The fieldwork was a large-scale undertaking that involved multidisciplinary teams, a wide variety of activities, and the coordination of various government departments, universities, and private institutions. The different sets of activities and the methods employed are described below. A summary of the results is given in Chapter 7.

Areas of Investigation

Stability of the moraine dams

a. Geological and geophysical properties using ground penetrating radar (GPR); this enabled location of buried ice and determination of the composition of morainic materials
b. Moraine geotechnical properties including size distribution, compaction, cohesion and friction coefficients
c. Geomorphological characteristics of the lake and surrounding area
d. Topographical survey of the moraine, the outlet, and the surrounding area including changes in the lake shoreline, and the position of the glacier terminus

Lake storage volume

A detailed bathymetric survey was used to calculate the lake storage volume, using either direct depth measurement or echo-sounding.

Potential external GLOF triggers

a. Observation of the associated glacier for hanging glaciers, glacial retreat, and other phenomena
b. Looking for possible ice avalanches, ice calving, rock and/or debris falls or slides, slope failures, and so on
c. Signs of seismic activity (possible earthquakes)

Hydrometeorological data

a. Measurements of discharge, flow velocity, and cross-sectional area
b. Meteorological data such as air temperature, relative humidity, radiation, wind speed, and direction
c. Electrical conductivity and temperature of the lake water
d. Hydraulic characteristics such as the steepness of the river, channel geometry, roughness coefficient, and seepage information.

Potential socioeconomic impacts

Dam break and flood routing models were calculated to help identify the potential downstream impact areas and elements at risk. The socioeconomic vulnerability was assessed by interviewing the people who lived in the areas identified by the model. The model and the interviews helped to estimate the following:

a. How the moraine dam might fail
b. Peak floods for various scenarios
c. Flood routing downstream
d. Flood hazard mapping and vulnerability assessment (physical)
e. Flood hazard, impact, and vulnerability assessment (socioeconomic)

Field Techniques

Topographical survey

All three lakes were mapped in 2009. This included the end moraines that dam them, together with their overflow channels, the lateral moraines, the lake shorelines, and the glacier termini. Mapping was carried out using a 'total station' (Sokkia and Pentax), a levelling process supported by a differential global positioning system (dGPS) (Leica), and other GPS instruments. The survey used additional benchmarks (BM) installed by different groups during earlier mapping projects to ensure that the resulting map was compatible with earlier maps of the area. Both the existing and newly established benchmarks were used to monitor vertical and horizontal changes in the surface features of the moraines, the lake shoreline, the position of the glacier terminus, and the surroundings over a period of time. Leica dGPS equipment (Leica #SR20, fixed and rover) had been used previously to tie benchmarks to WGS 1984 coordinates. Attempts were made to reconcile field benchmark data with the national WGS 1984 data set (Tsho Rolpa and Thulagi). It is hoped that this will ensure that future work can be tied to the reference benchmarks employed in the present study when the differential global positioning system (dGPS) is not available or not used. The ellipsoidal elevation data obtained from differential calculation of dGPS were corrected by geoid adjustments, which were different for the various geographical locations as per the correction factors of national geodetic survey departments. The WGS 1984 benchmarks for Tsho Rolpa (T1) and Thulagi (G16) were determined by taking several repeat observations and using the mean value. The accuracy of the measured vertical position after repeat observations over three to four hours (battery constraints in cold, high altitudes > 4000m) for several days was two to three metres, whereas the accuracy of the horizontal position was 1-1.5 m for single frequency L1.

The dGPS instrument was used to carry out survey work using the WGS 1984 coordinates with the advantage that these can be referred to and compared in future survey work using common national coordinates. However, the available topographical maps from the Survey Department of Nepal are based on national coordinates, which differ from the WGS 1984 survey. Work with the 'total station' was faster and more reliable (with an accuracy of one second). Observations with the dGPS took longer as there were constraints due to the battery draining within 3 to 4 hrs in the cold narrow valleys and an insufficient number of satellites being available during periods of observation. When elevation differences between two benchmarks were calculated using dGPS, the accuracy of the relative height of the benchmarks improved to 0.5 m.

Bathymetric mapping investigation

The bathymetric survey was carried out from an inflatable boat with an outboard motor. The observations were used to estimate lake storage volume; to evaluate the lake bottom condition near the outlets; and to assess stability of the end moraines below the lake surface. The positions (X and Y coordinates or grid) of the bathymetric observation points were recorded using a GPS. Depth measurements were made using the echo-sounder equipment 'Ninglu DS 2008' in Thulagi and Tsho Rolpa, and an old-fashioned (but effective) method of dropping a weighted line in Imja Tsho (because the echo sounder was malfunctioning). The bathymetric measurements were taken 5 -10 m from shorelines for safety reasons to avoid active sliding of the inner moraine slopes. Bathymetric maps were then prepared and the surface area and storage volume of the lakes were calculated.

Hydrometeorology

DAVIS Automatic Weather stations were installed near the survey camps and operated for the duration of the field studies. This equipment functioned well during the Tsho Rolpa expedition, but malfunctioned at Thulagi Lake and Imja Tsho. Weather data were collected for 16 days at Imja Tsho (11-28 May 2010). Heavy snowfall lasting 36 hours (May 23rd and 24th) caused a loss of precipitation data because the rain gauge was not adapted for snow.

Lake discharge measurements were made using dye tracers and conductivity methods. For the dye tracer study, environmentally neutral sulphorhodamine G (SRG) tracer was introduced into the lake outlet streams for a defined period of time at a constant rate, and water samples were collected downstream at fixed time intervals. The tracer concentrations in the samples were evaluated later in the laboratory using spectro-fluorometry and the results used to calculate discharge. The salt dilution method was used to measure turbulent flow. A salt water solution was poured into the water and, after ensuring homogeneous mixing, electrical conductivity measurements were made at downstream locations at regular intervals to evaluate the salt concentrations – the discharge was then calculated.

Engineering geology and geophysics

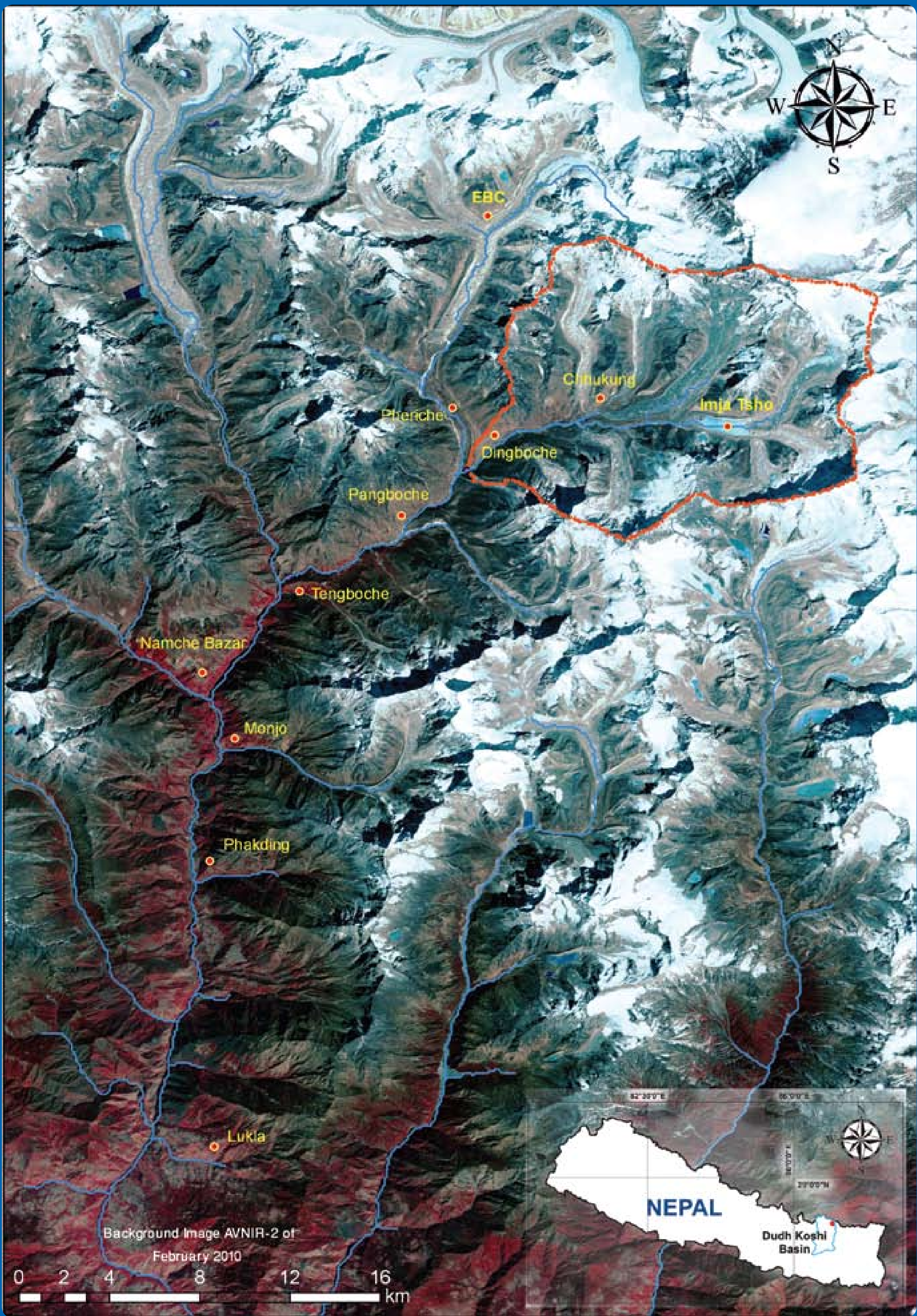
Engineering geological studies were carried out to evaluate the geological settings of the glacial lakes, glaciers, moraines, and the surrounding area. The composition of rocks as well as geological and geomorphological processes and landforms were evaluated. Various landforms, and processes were also analysed. The property of the surface material was estimated for d90, d60, and d10, porosity, and void ratios. Unit weights were estimated subjectively. Angles of repose were measured at several slope locations for input into dam stability determinations and GLOF modelling.

Geophysical investigations were carried out for detection of buried ice both within the moraines and below the lakes. A RAMAC GPR instrument with a 100 MHz antenna was used for the GPR surveys. In the rough and unstable field conditions of Tsho Rolpa, wide angle reflection and refraction survey lines were selected. Due to malfunctioning of the GPR equipment and bad weather, only a few measurements were made at Imja Tsho.

Modelling and socioeconomic analysis

A numerical model was used to simulate GLOF flooding in the downstream valleys and to evaluate socioeconomic impacts for vulnerability assessments. Details of the methodology are provided in Chapters 8 and 9.

Figure 7.1: **Location of Imja Tsho and drainage area of the Imja Khola**



7 Results of the Field Investigations

The results of the field investigations of the three glacial lakes are presented below for each lake individually, and then discussed together in a summary section. All results from previous research were reviewed prior to the field visits. This pre-existing knowledge is presented as a preamble to each section.

Imja Tsho

Imja Tsho is located in the eastern Nepal Himalayas at 27°54′ N latitude and 86°56′ E longitude. It has formed on the lower tongue of the Imja Glacier, south of Lhotse (8,501 m) and Island Peak (Imjatse) (6,173 m) (Figures 7.1 and 7.2).The lake surface lies close to 5,000 metres above sea level. It is drained through the end moraine that forms the lake dam by the Imja Khola, one of the main tributaries of the Dudh Khosi.

An unusually heavy and unseasonal snowfall hampered the fieldwork which was also beset by the malfunctioning of the GPR (ground penetrating radar), automatic weather station (AWS), and echo-sounding equipment. Despite these problems sufficient information was collected to satisfy the expedition's original objectives.

Development of Imja Tsho

Several studies have been carried out on Imja Tsho and its downstream areas (Hammond 1988; Yamada 1992; Watanabe 1992; Watanabe et al. 1994, 2009, 2011; Kettelmann and Watanabe 1998; DHM 2001a, 2001b; Sakai et al. 2005, GEN 2006). The lake was first referred to in the literature by Vuichard and Zimmermann (1987) who used the name 'Pareshaya Tsho', although the derivation of this is not known. Hammond (1988) referred to it as 'the Imja Glacier lake'. This became 'Imja Glacier Lake' (Watanabe et al.1994). It was mentioned as 'Imja Cho' in the topographic map prepared by the Survey Department of Government of Nepal. There was some reluctance to use the term Imja Tsho, or Imja Lake, because neither variation had been formally approved by the relevant Nepalese authority, but both have since come into common usage by default. This minutiae of toponymic detail is included because Imja Tsho has attracted almost world-wide attention due to its assumed extreme danger.

Ground photographs taken in the 1950s demonstrate that, except for several small melt ponds on the glacier surface, no lake existed at that time. The photographs were originally credited to Professor Fritz Müller who served as the 'scientific wing' of the 1956 Swiss Expedition to Everest and Lhotse and who was responsible for the first glaciological research in the Khumbu; however, they may have been taken by Erwin Schneider who was responsible for the first 1:50,000 map of the Mount Everest region. (The accreditation is obscured by the fact that Schneider loaned Müller his photo-theodolite; the theodolite was definitely used to take the photographs of the Imja Glacier, but this does not clearly identify the photographer.)

By 1984 a lake of approximately 0.4 sq.km had formed. The first major step was the acquisition of high quality stereoscopic photographs of the Imja Glacier. They were obtained on the special flight missions directed by Dr Bradford Washburn and Dr Barry Bishop as part of the production process for the 1988 1:50,000 map of the Mount Everest region sponsored by the National Geographic Society. Dr Washburn provided Professor Ives with copies of the stereo-pair and this prompted the systematic collection of all available photographs so that the history of the development of the lake could be documented. Several valuable photographs were provided by Professor K Higuchi of Nagoya University who had led a series of Japanese glaciological expeditions to the Khumbu from the 1960s to the 1980s. The photographs were made available to Ms June Hammond, a graduate student who analysed them as part of the work for her Master's thesis (Hammond 1988). For the first time, it was possible to draw a series of maps that could demonstrate the progressive evolution of the 1956 melt-ponds to a significant and potentially threatening lake by 1984. Since that time there has been continuing research on the Imja Tsho that continues to the present day. The main results are summarised below.

Figure 7.2: **Overview of Imja Tsho showing the lake (centre), outlet channel, ponds, side valleys, and surroundings 24 April 2009**

Watanabe undertook fieldwork in the upper Imja Khola as part of the research for his doctoral dissertation (Watanabe 1992). He continued field observations together with colleagues from Hokkaido University and subsequently with Dr Alton Byers up to the time this report went into production (Watanabe et al. 1994, 2009, 2011). Yamada (1992) directed field research on Imja Tsho (25 March to 12 April 1992) as part of a Japan International Cooperation Agency (JICA) and WECS technical cooperation agreement. Concurrent research by Sakai et al. (2003; 2005) added additional knowledge about the lake's enlargement, its bathymetry, its total volume in different years, and the condition of its end and lateral moraines. Imja Tsho also became part of ICIMOD's large-scale remote-sensing survey and inventory of glaciers and glacial lakes in Nepal (Mool et al. 2001a). Hambrey et al. (2008) studied the characteristics of four glaciers in the Khumbu region, including Imja Glacier and Lake. Watanabe et al. (2009) produced a detailed contour map, together with reconstruction of variations in lake level between 1964 and 2006-2009. By 2006 the previous rapid enlargement of the lake westward towards its end moraine dam had slowed to as little as six metres a year; but it continued to expand rapidly eastward as the glacier terminus retreated. Its total length in 2009 was calculated at 2.2 km (Watanabe et al. 2009).

During the early stages of the research discussed above, partly because of incomplete geophysical data, and partly because of the apparently alarming rate of its expansion, Imja Tsho was considered to be in danger of catastrophic outburst. As more data became available, however, particularly the observations showing a major reduction in the rate of lake expansion westwards into the end moraine and other data demonstrating that the lake level had dropped by 37 metres (between 1964 and 2006), the danger of outburst came to be regarded as far less than originally expected.

The field investigations reported here showed a further increase in lake area to 1.012 sq.km.

Figure 7.3 shows the progressive development of Imja Tsho between 1962 and 2010.

Figure 7.3: **Development of Imja Tsho from 1962 to 2010 based on Corona (1962) images, Topographical Map (1967), Landsat MSS (Oct 1975), Landsat TM (April 1984, Dec 1989), Aerial photo (1992), LISS 3 (Jan 1999), Landsat ETM+ (Oct 2001, Nov 2005), ALOS PRISM (2006), AVNIR-2 (Nov 2007, Nov 2008, and Mar 2009), Field Survey (WECS 1992, DHM 1997, GEN 2002 and ICIMOD 2009), and EO1_ALI (USGS) Oct 2010)**

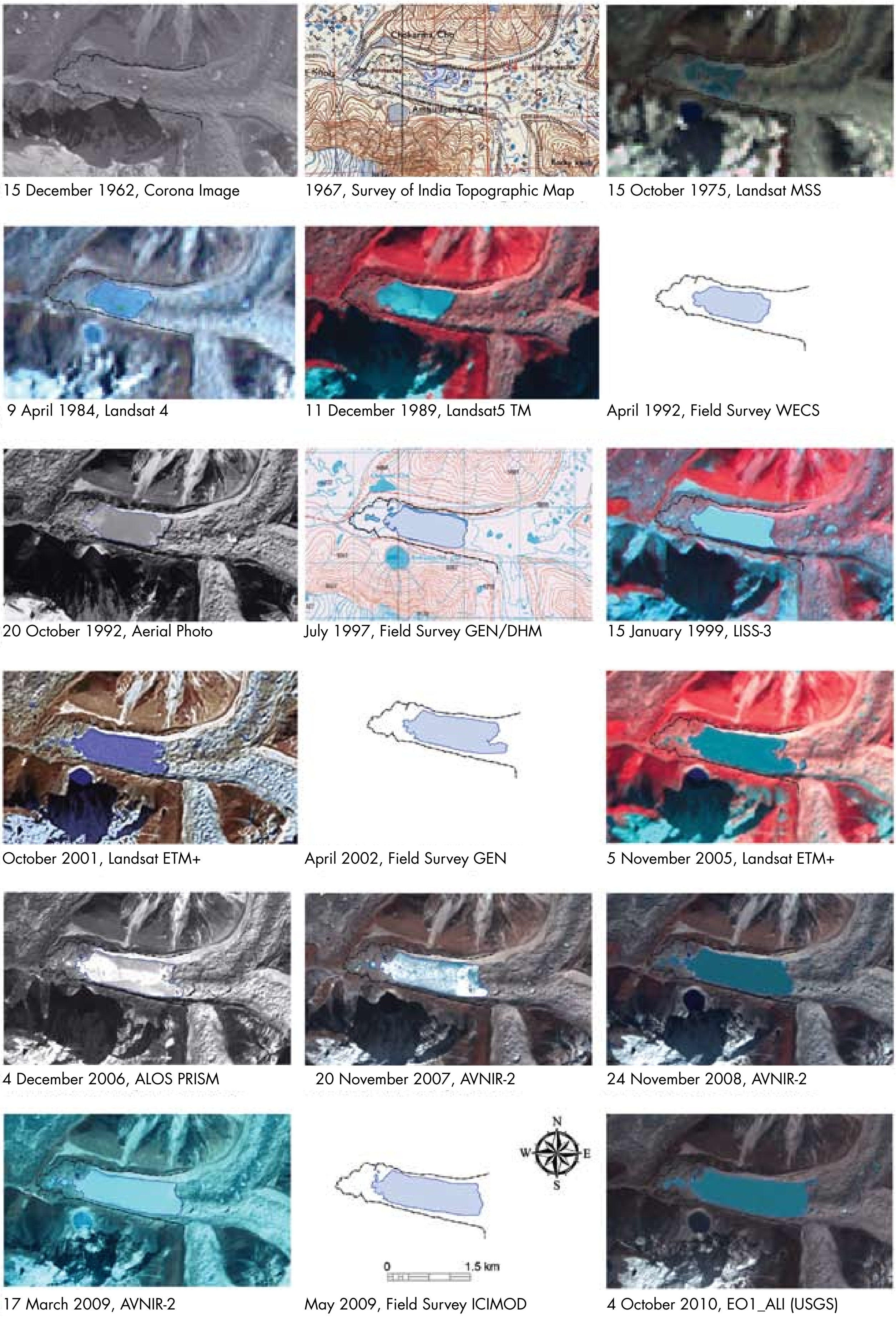
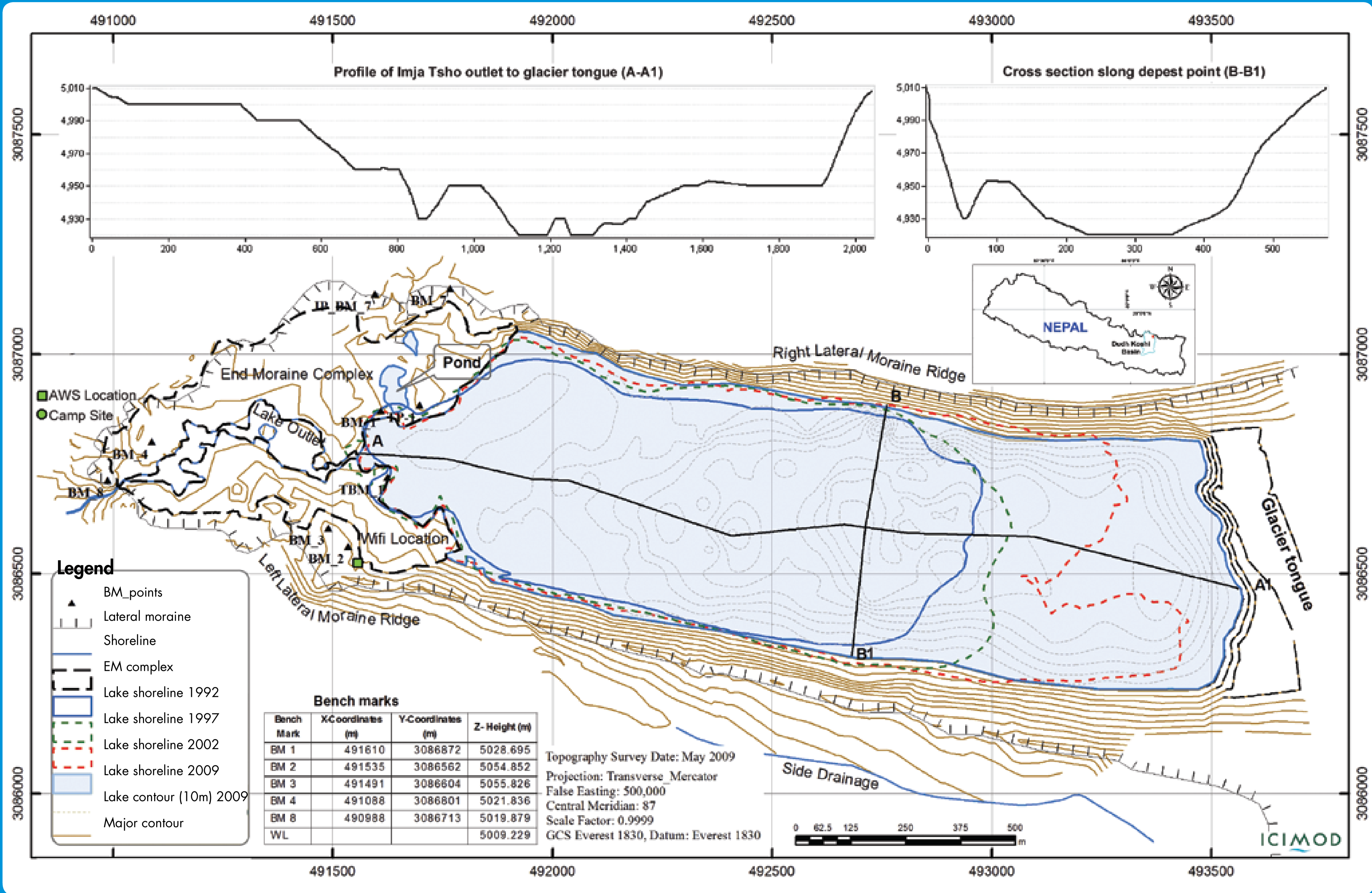


Figure 7.4: **Bathymetric and topographic map of Imja Tsho showing the longitudinal profile and cross-section along the deepest point**



Bench marks

Bench Mark	X-Coordinates (m)	Y-Coordinates (m)	Z- Height (m)
BM 1	491610	3086872	5028.695
BM 2	491535	3086562	5054.852
BM 3	491491	3086604	5055.826
BM 4	491088	3086801	5021.836
BM 8	490988	3086713	5019.879
WL			5009.229

Bathymetric investigations

The first bathymetric investigation of Imja Tsho was conducted by Yamada in 1992 under the WECS/Japan International Cooperation Agency (JICA) technical cooperation research expedition (Yamada 1992).

In 1992 the lake area was 0.60 sq.km and its volume 28 x10^6 cu.m (Yamada 1992). The field investigations showed that by 2009 the lake area had increased to 1.01 sq.km and the storage capacity to 35.5 x10^6 cu.m; the maximum depth obtained was 96.5 m. The bathymetric and topographic maps from the field survey are shown in Figure 7.4. The lake area continues to increase, but with a reduction in the rate of growth since 2001. At the same time, the actual level of the lake fell by 0.3 to 0.4 m/yr between 2001 and 2009, while benchmarks towards the end moraine subsided by about 0.1 m/yr (GEN 2006 and ICIMOD Field Survey 2009). The level differences between the benchmarks on the lateral moraines are becoming less, although not uniformly, indicating irregular settling of the surface of the moraine dam over the last seven to eight years.

The contemporary expansion of Imja Tsho is primarily towards the east as the relatively warm lake water melts back into the glacier and accentuates the collapse of blocks of ice from the cliffs that form its terminus. (Yamada 1992; DHM 2001a; Sakai et al. 2005; GEN 2006; and present study). The western margin of the lake close to the end moraine has also expanded, although the position of the outlet has remained more or less unchanged. Watanabe et al. (1994) reported a rapid westward expansion towards the end moraine between 1989 and 1994. Shifting of the outlet channel was also reported (Watanabe 2009). This is not supported by Yamada (1992) nor by the present field investigation, and no significant change between 1992 and 2009 can be detected from the satellite images (Figure 7.4).

Hydrometeorology

The nearest hydrometeorological station to Imja Tsho is located in Dingboche Village about 10 km to the west and 700 m lower in elevation. The station was established in 1988 by the Department of Hydrology and Meteorology (DHM), Government of Nepal. Hydrometeorological data were semi-automatically recorded until 1999 and manually thereafter. Imja Tsho drains through the 500-metre extent of end moraine to form the Imja Khola (river). Experimental measurements showed that the lake discharged at a rate of 0.4 cumecs during the month of May with little diurnal variation. A seasonal maximum discharge of 5.2 cumecs was observed between June and September and a seasonal minimum of 1.1 cumecs between December and February (measured at Dingboche). The discharge increased gradually from April to August and decreased from September until the onset of the winter season.

Meteorological data were obtained from the Dingboche station for the period from 1987 to 2004. The average annual mean temperature for this period was -0.8°C; with an average annual increase of 0.07°C.

August is the month with highest rainfall followed by July. The average precipitation in the area during the monsoon period (June - September) is 273.4 mm and during the dry season (December - February) 13.1 mm. Maximum primary and secondary solar radiation of 267 W/m^2 and 265 W/m^2 were recorded during July and May respectively.

Geophysical investigations

The geophysical investigations showed the existence of dead-ice blocks within the end moraine, together with multiple thermokarst features. In places the ice was visible at the surface. The presence of slowly melting blocks of ice has been corroborated by Yamada (1998a) and Reynolds (2006) who demonstrated the presence of dead ice masses of different sizes in the end moraine. Hambrey et al. (2008) came to a similar conclusion based on geotechnical surveys. Limited radarogram analysis based on a ground penetrating radar survey along the shoreline of Imja Tsho showed that the moraine contains patches of unconsolidated materials made up of big boulders that create large voids.

Glacier observations

Lhotse Shar, Imja, and Amphulapcha are the glaciers associated with Imja Tsho. Lhotse Shar Glacier flows southwestward from the south face of a high mountain ridge dominated by Peak 38, due east of Lhotse (8,501 m) and Lhotse Shar (8,386 m). The Imja Glacier is oriented slightly north of due west; it originates on the northwest face of Baruntse (7,168 m) and coalesces with Lhotse Shar Glacier. Amphulapcha Glacier flows due north and is barely connected with its two neighbouring glaciers. Imja Glacier is heavily covered with debris and has a gentle gradient in its lower section. In the 1960s, its total length was about 10.8 km; this had been reduced to to 8.4 km by 2001, giving a rate of retreat, excluding the dead-ice/lake section, of 59 m/yr between 1960 and 2001 and of 74 m/yr from 2001 to 2006 (Bajracharya et al. 2007). Its ablation zone faces west. The lower section of the glacier ends in ice cliffs about 40 to 45 m high overlooking the lake. There are numerous crevasses and collapse features (Figure 7.5). The collapse features are thought to be related to the high melting rate of the glacier tongue due to strong solar radiation, the presence of supra-glacial melt-ponds, and the very slow flow rate of the glacier. Periodically, ice calves from the terminal cliff and drops into the encroaching lake. At the opposite end of the lake, the melting of ice blocks within the end moraine is thought to be slow because of the existence of isolated ponds of clear water. Watanabe et al. (2009) examined the condition of the lake outlet channel and considered it to be fairly stable.

Discussion

During the field investigation, inspection of the surroundings showed that there is little possibility of a rock-fall or rock-slope failure that could threaten the stability of the lake. The end moraine damming the lake is 536 m wide and 567 m long; any overtopping waves would have to overcome this wide barrier. The waves generated when ice calving occurs at the fractured glacier terminus are not considered sufficiently large to overtop this terminal moraine. Surge waves were observed following calving from the glacier terminus during the field investigations; by the time they reached the end moraine they were only around half a metre high. The possibility of an ice avalanche into the lake that could trigger a GLOF is also not considered to be very likely at present. In general, the outer slopes of the lateral moraines are gentler than the inner slopes and are abutted by parallel push moraines, wide lateral moraines, or vegetation cover. The inner sides of the lateral moraines that contain Imja Tsho are steep and highly eroded, hence loose sediment falls down into the lake.

The lateral moraines become narrower and lower towards the west as the end moraine is approached and the lake becomes wider. Hence, regular monitoring of the lateral moraines is essential. We recommend that especially the right lateral moraine

Figure 7.5: **Imja glacier terminus from a distance** (below 24 May 2009) **and closer view** (above right 23 May 2009) **showing thick debris cover and numerous transverse crevasses and collapse features**

be monitored because some portions of it are at risk of breaching since they are comparatively narrow and low and contain unconsolidated material. It is also important to note that the end moraine is subsiding as the buried ice melts, and this melting leaves behind coarse materials and potentially large voids which could also reduce stability. Further study is required to assess the likelihood of a larger than expected icefall from the glacier terminus and the potential impact of the resultant surge. In other parts of the world, temporary blockage of lake outlets through moraines due to freezing water and snow barriers or lake ice debris have led on several occasions to outbursts or related hazards. At Imja Tsho, the flow from the lake is uninterrupted, even though it freezes during the winter and an ice layer up to 70 cm thick is formed on the lake itself. This was determined from bore holes during the earlier bathymetric survey (GEN 2006).

The peak outflow from Imja Tsho during the monsoon is accommodated by the existing outlet, although it is not known how much is contributed by glacier melt and how much by local drainage. The present outlet channel is long and wide and flows through the end moraine, but is narrow when it leaves the end moraine complex.

A thorough investigation of the moraine condition is required in order to identify appropriate mitigation measures and whether they are needed. The lake and surroundings, especially the lake outlet, also need to be monitored. This should include discharge from the outlet, any seepage flows from the end and lateral moraines, and contributions from glacial meltwater and englacial flow. Regular bathymetric observation is also needed, including measurement of absolute ground movement to assess moraine dam stability.

Further detailed ground penetrating radar (GPR) investigations are required around the end and lateral moraines of Imja Tsho as there are many exposed thermokarst features along the channel which will play a role in determining the stability of the moraine. The possibility of linking any mitigation measures that might be undertaken in the future to development of a small hydroelectric facility to supply energy to downstream settlements should be considered (this would require hydro-engineering expertise). Such a linkage should be a good way to incorporate input from the local people and would strengthen the protection afforded by early warning systems.

Tsho Rolpa

Tsho Rolpa is located in the central Nepal Himalayas at 27°52′ N latitude and 86°28′ E longitude, at an altitude of 4,546 masl. It forms the headwaters of Rolwaling Khola, a tributary of the Tama Koshi river in Dolakha district (Figure 7.6).

The 1991 GLOF from Chubung (a small supra-glacial lake on the surface of the Ripimoshar glacier adjacent to Tsho Rolpa) alarmed local communities because of the damage it caused 10 km downstream at Bedding village in Rolwaling valley. In 1992, R J de Meijer and E M Smit made a layman's assessment of the hazard of the potential outbreak from Tsho Rolpa (Meijer and Smit 1992). Damen (1992) carried out the first scientific investigations of Tsho Rolpa and made recommendations for measures to lower the water level and to monitor water-level fluctuations. Following the publication of this report, the local community continued to be concerned. WECS led a preliminary field study of Tsho Rolpa with assistance from JICA from 1993 to 1997 (WECS 1993, 1994, 1995, a, b, d, e, 1996, Yamada 1993, 1998; RGSL1994, 1996, 1997; Mool 1995). This was followed by several other studies carried out by professionals and students from different countries on various aspects of Tsho Rolpa. The results were summarised in a number of publications, e.g., Modder and van Olden (1995), Reynolds Geosciences Ltd (1994, 1996, 1997), Mool (1995), Budhathoki et al. (1996), Chikita et al. (1997), and Yamada (1993, 1998). In addition, since Tsho Rolpa was considered to be a potential threat to the Khimti Hydroelectric Project, which was then under construction, it was also studied by engineers from the hydroelectricity project between 1994 and 1996.

Development of Tsho Rolpa

Development of Tsho Rolpa is shown in Figure 7.7. During the late1950s, Tsho Rolpa existed only as a group of six small supra-glacial ponds. Between 1957 and 1959 its area was about 0.23 sq.km. The lake grew continuously from the beginning of the 1960s and by the 1990s it had enlarged to such an extent that it was considered to be on the verge of breeching its end moraine. Satellite images (MOS1 MESSR) showed that it had grown to 1.27 sq.km by 1990 and 1.55 sq.km by 1999. Mitigation work was completed in 2000; this included construction of a gated outlet channel that

Figure 7.6: **Location of Tsho Rolpa showing catchments of Rolwaling valley and major settlements along the Tama Koshi and Rolwaling valleys**

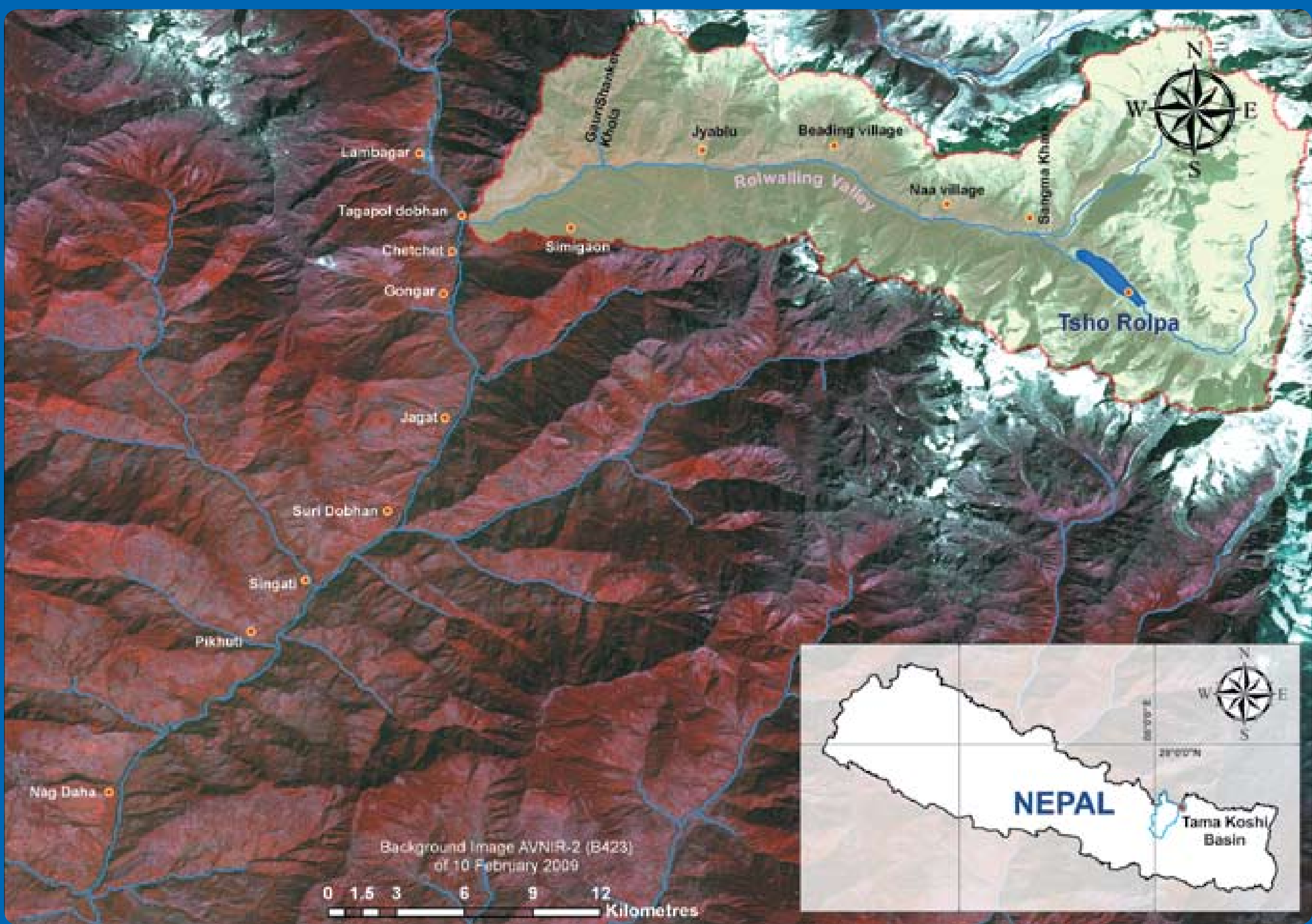


Figure 7.7: **Development of Tsho Rolpa from 1957 to 2009 based on Topography Map (1957-59), Schneider Map (1960-68), Corona (1973), Landsat MSS (1975), SpaceLab IR (1983), Landsat TM (1991), Aerial Photo (1992), LISS-3 (1999), Landsat ETM+ (2000), AVNIR-2 (2007), WECS Field Survey (1993-94) and ICIMOD (2009)**

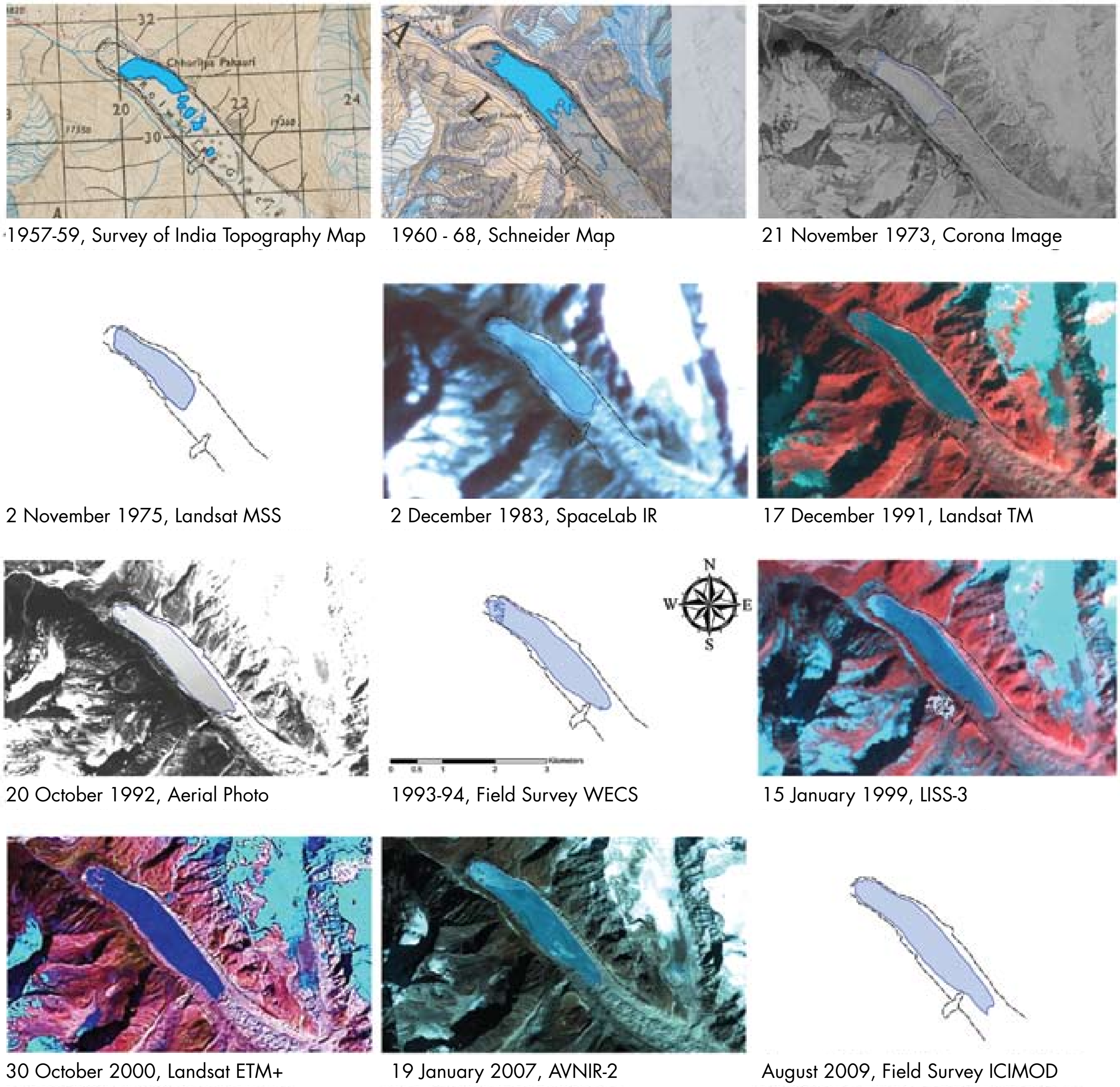
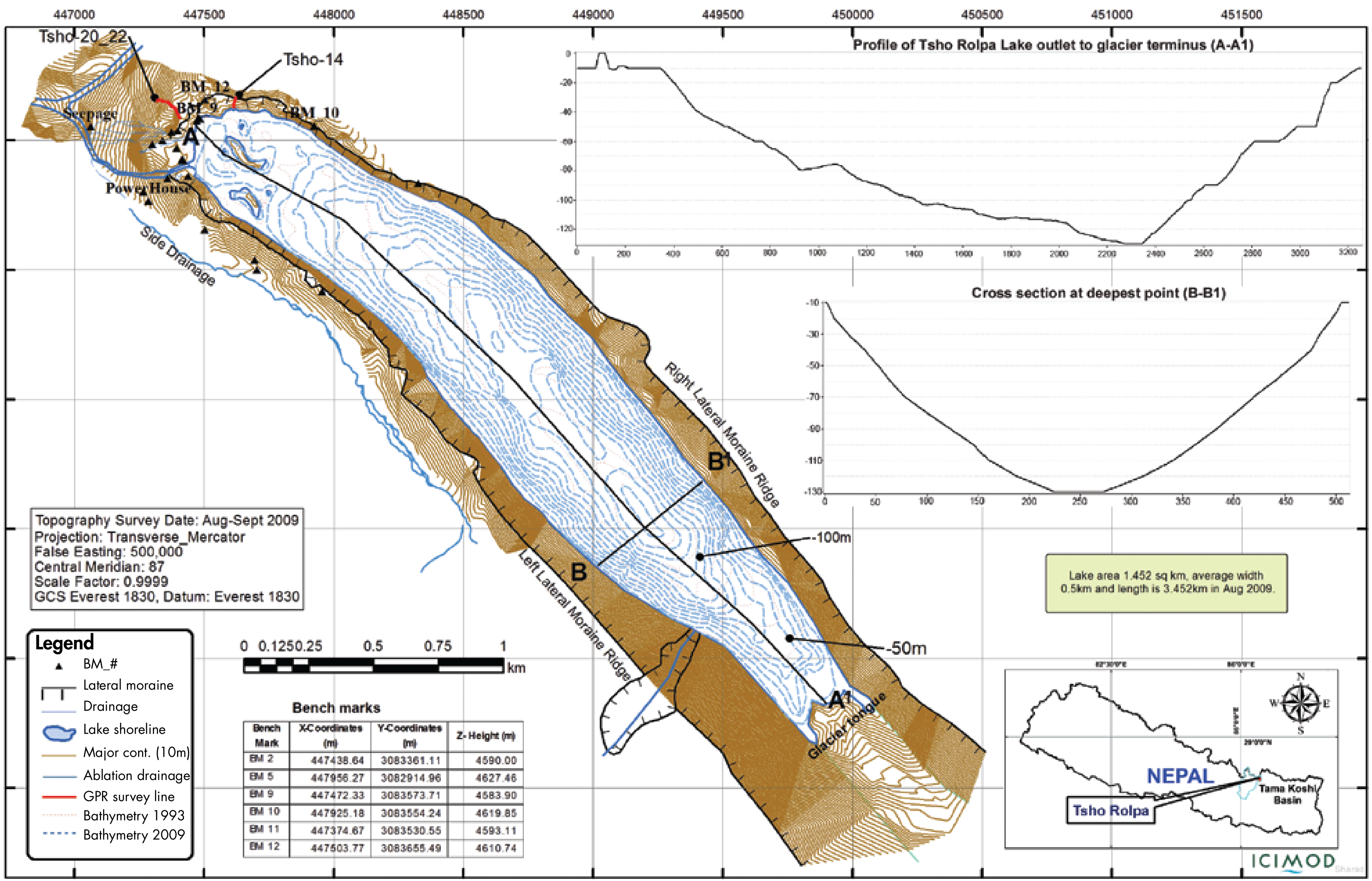


Figure 7.8: **Bathymetric and topographic map of Tsho Rolpa showing the longitudinal profile and cross-section through the deepest point**



Bench marks

Bench Mark	X-Coordinates (m)	Y-Coordinates (m)	Z-Height (m)
BM 2	447438.64	3083361.11	4590.00
BM 5	447956.27	3082914.96	4627.46
BM 9	447472.33	3083573.71	4583.90
BM 10	447925.18	3083554.24	4619.85
BM 11	447374.67	3083530.55	4593.11
BM 12	447503.77	3083655.49	4610.74

reduced the lake level by three metres. As a result, by 2000, satellite images (Landsat ETM+ 2000) showed that the area had decreased to 1.53 sq. km. Growth of the lake after 2000 was slow. The 2005 satellite image (Landsat ETM+ 2005) indicated an area of 1.535 sq.km and the 2007satellite image (AVNIR-2) an area of 1.538 sq.km. Tsho Rolpa is thought to be one of the most dangerous lakes in Nepal; it is continuously monitored by the Department of Hydrology and Meteorology (DHM).

The current field investigations indicated a length of 3.45 km and an area of 1.537 sq.km.

Bathymetric investigations

Bathymetric investigations of Tsho Rolpa began with the work of WECS in 1993 and have been repeated by a number of investigators since (WECS 1993; 1994; 1995 d; 1996; Yamada 1998a; and DHM 2002 a, b, 2003 b, 2004; Shrestha et al. 2004).

The field investigations showed that the lake has progressively deepened (Figure 7.8). The rate of deepening between Lama Island and Instrument Island was estimated to be 0.234 m/year by Chikita et al. (1997), while Sakai et al. (2000) provided a figure of 0.255 m/year. Comparison of unpublished field data from WECS 1993 and 1994 and field data from the current investigation showed that benchmarks at Lama Island, Instrument Island, and Middle Island are sinking at 0.24 m/year, 0.61 m/year, and 0.49 m/year respectively. The rate of sinking increases from northwest to southeast across the end moraine with an average rate of 0.44 m/year. The deepest part of the lake is sinking at approximately 0.37 m/year, and the average lake deepening rate (including islands and deepest points) is about 0.43 m/year.

Hydrometeorology

Meteorological data are available for Tsho Rolpa for the period from 1993-1996 (Yamada 1998a) but there is a data gap for a considerable part of 1993-94. Unpublished meteorological data for 1999-2004 from the Department of Hydrology and Meteorology, Nepal, were also used for hydrometeorological analysis. Based on these data sources, the daily average air temperature in the Tsho Rolpa area from 1993 to 2004 was estimated to be 0.3°C, with an increase in mean annual air temperature (MAAT) of 0.074° C between 1998 and 2004. This trend is similar to that determined for the Imja Tsho area. The lack of long-term data makes it impossible to predict future trends.

On average, more than 60% of the annual rainfall in the Tsho Rolpa area occurs during the monsoon period from mid-June to mid-September. In the period 1993-2004, the maximum annual precipitation was 829 mm (2004) and the minimum 355 mm (1993). The annual mean solar radiation was 269 W/m^2 in 1994 and 237.6 W/m^2 in 1995. The minimum solar radiation is in December/January (recorded monthly mean 158-180 W/m^2) and the maximum in May just before the monsoon season (356-364 W/m^2) (Yamada 1998a). Yamada (1998a) describes the winds in Tsho Rolpa as quite stable with daily mean values of 1.7 to 2.9 m/s throughout the year.

The capacity of the Tsho Rolpa artificial outlet channel is 35 cumecs, which is roughly twice the maximum monsoon discharge of 18 cumecs measured by the automatic weather station in 1993-94. The maximum and minimum discharge values measured from 1-12 Sept 2009 during the field investigation were 3.54 and 1.89 cumecs.

The derived empirical relationship (rating equation) between the lake-water level and the measured discharge was

$$Q = \mathrm{Exp}\,(4.428) \times (H-H_0)^{1.655}$$

where, Q is the discharge in cumecs, H is the final height (water-level gauge) in m, and H_0 is the initial height (water-level gauge) in m.

Geophysical investigation

An initial electrical resistivity exploration by WECS detected the existence of dead-ice blocks covered by debris at or near the surface of the end moraine (WECS 1995b). Later measurements showed that the dead ice had since melted down to a level at least 5 to 10 m below the surface (RGSL 2000, DHM 2003a, 2003b).

This finding was corroborated by the (GPR) ground-penetrating radar survey during the current field investigation. The GPR survey showed that the northwestern section of the end moraine near the shoreline (Tsho 20-22 and Tsho 14 in Figure 7.8) contained dead ice between BM 12 and BM 10; the depth of its upper contact lay between 14.5 and 17 m below the surface. In other words, whereas there was ice at or near the surface during the WECS 1994 survey, the ice is now 14.5 -17 m below the surface. There is a transitional zone about 0.5 metre thick exhibiting the characteristics of a moist sandy layer between the debris and dead ice.

The radarogram analysis of the Tsho Rolpa end moraine showed that most of the dead ice cores were located in dry, medium to large grain-size, sediments; the end and lateral moraines consisted of coarse and very coarse unconsolidated materials. Large boulders were found about six metres below the surface and were underlain by medium coarse sediments. The presence of large boulders creates large voids, which is a matter of concern for stability.

Glacier observations

The Trakarding Glacier is in contact with Tsho Rolpa (Figure 7.9). It is a debris-covered glacier, with a debris thickness varying from a few centimetres to tens of metres. The whole length of the Trakarding Glacier lies in the ablation zone; the clean Trambau Glacier, which is fed by snow and ice from Mt. Bigphera Go Shar and Go Nup, feeds the Trakarding Glacier. The Trambau Glacier is oriented towards the south, and then continues flowing northwest as the Trakarding Glacier.

In 1960 the Trakarding glacier was about 22.17 km long. This was reduced to 18.62 km in 2009 as measured in the field studies, giving a retreat rate of about 72.3 m/yr between 1960 and 2009, slightly higher than the rate of 66 m/yr reported for 1957 to 2000 (WECS 1993; Bajracharya and Mool 2005) and of 65.7 m/yr between 1993 and 1994 (Yamada 1998a; Chikita et al. 1997). A comparison of the results of the current field investigation with those of the WECS investigation of 1993 and 1994 showed that the lake had extended by 17 to 20 m/yr since 1993. The terminus of the

Figure 7.9: **Glacier terminus with thick debris cover in contact with the Tsho Rolpa. Thermokarsts are exposed on both the left and right lateral moraines which are also in contact with the glacier terminus, 11 September 2009**

Trakarding glacier descends into the Tsho Rolpa at 4,546 masl. In 1997, there was a nearly vertical ice wall about 30 to 40 m above the lake at the terminus; this has now been reduced to a surface slope towards the lake with a height of only a few metres.

There are three hanging glaciers on Mt. Tsoboje situated high above the right side of Tsho Rolpa. Over the years these have not been considered a serious threat in terms of snow and ice avalanches; nevertheless, it is important to continue monitoring them on a regular basis to assess the possibility of a surge wave being generated by ice falls from the glaciers. The stability of these steep glaciers could not be judged during the current field investigation.

Discussion

Tsho Rolpa has a narrow end moraine in which there is a possibility of piping developing (formation of water channels inside the moraine due to seepage, and leading to instability). This needs to be investigated. Seepage was detected at the toe of the outer wall of the moraine dam, but it was found later that it was not coming from the main lake. Follow up investigations will be needed to identify the source of the seepage which could be the melting of dead ice or from local drainage. Regular monitoring will also be needed as discharge and debris from side valleys drop into the lake.

Temporary blockage of the lake outlet over the moraines by freezing water and snow barriers, or lake ice debris is very unlikely because the lake outlet has a wide artificial channel through the moraine dam that functions as a spillway. During the field investigation, the team noted that the gated artificial outlet channel was functioning satisfactorily, but they also noted vibrations in the anchor blocks as well as subsidence in the gabion walls. These two features should be monitored regularly.

Monitoring of the hanging glaciers and the likelihood of them breaking off is one of the major practical challenges in the hazard assessment of Tsho Rolpa. They are clearly visible as they have a limited area. There is a permanent office building with regular staff at Tsho Rolpa who could be trained to make regular inspections of the hanging glaciers and other changes in the condition of the lake, moraine dam, and vicinity as a part of monitoring measures. Climatic data should be recorded and monitored regularly in the Tsho Rolpa area, particularly extreme climatic events and their impacts.

Thulagi Lake

Thulagi Lake is located in western Nepal at 28°29′ N latitude and 84°29′ E longitude at an altitude of 4,044 masl. The lake lies at the end of the Thulagi Glacier to the southwest of Mount Manaslu in the headwaters of the Dona Khola, a tributary of the Marsyangdi river (Figure 7.10).

Thulagi Lake has attracted much attention because several hydropower projects are planned downstream of it in the Marsyangdi river basin. Two projects – the Marsyangdi Hydropower Project and the Middle Marsyangdi Hydropower Project – have already been commissioned and an Upper Marsyangdi Hydropower Project is in the planning stage.
The first field-based investigation of Thulagi Lake was carried out by WECS in 1995 (WECS 1995 c). It was followed in 1996 by a joint investigation by DHM and the Federal Institute for Geosciences and Natural Resources (BGR), Hannover, Germany (DHM 1997). Additional studies were made in 2000 by the Nepal Electricity Authority (NEA), DHM, and BGR (NEA/DHM/BGR 2001).

Development of Thulagi Lake

Thulagi Lake began to form about 50 years ago when small supra-glacial lakes began to enlarge and coalesce. It is now more than 2 km long. Its development was described by Mool and others in a preliminary report prepared from a field survey carried out in 1995. A comparison between topographical maps of the Survey of India from 1958 and the 1995 WECS field results indicated that the lake area had increased in size from 0.22 to 0.76 sq.km and in length from 0.6 to 1.97 km, but that there was not much change in width (WECS 1995c). The present field investigations showed that from 1995 to 2009, the length of Thulagi Lake had again increased from 1.97 to 2.54 km, and the area from 0.76 to 0.94 sq.km.

The development of the lake since 1990 was calculated using topographic maps, satellite images, and the results of the present and previous field investigations (Figure 7.11). The lake is expanding into the glacier terminus, causing it to retreat and calve (Figure 7.12).

Figure 7.10: **The location of Thulagi Lake, catchment of Dona Khola, and major settlements**

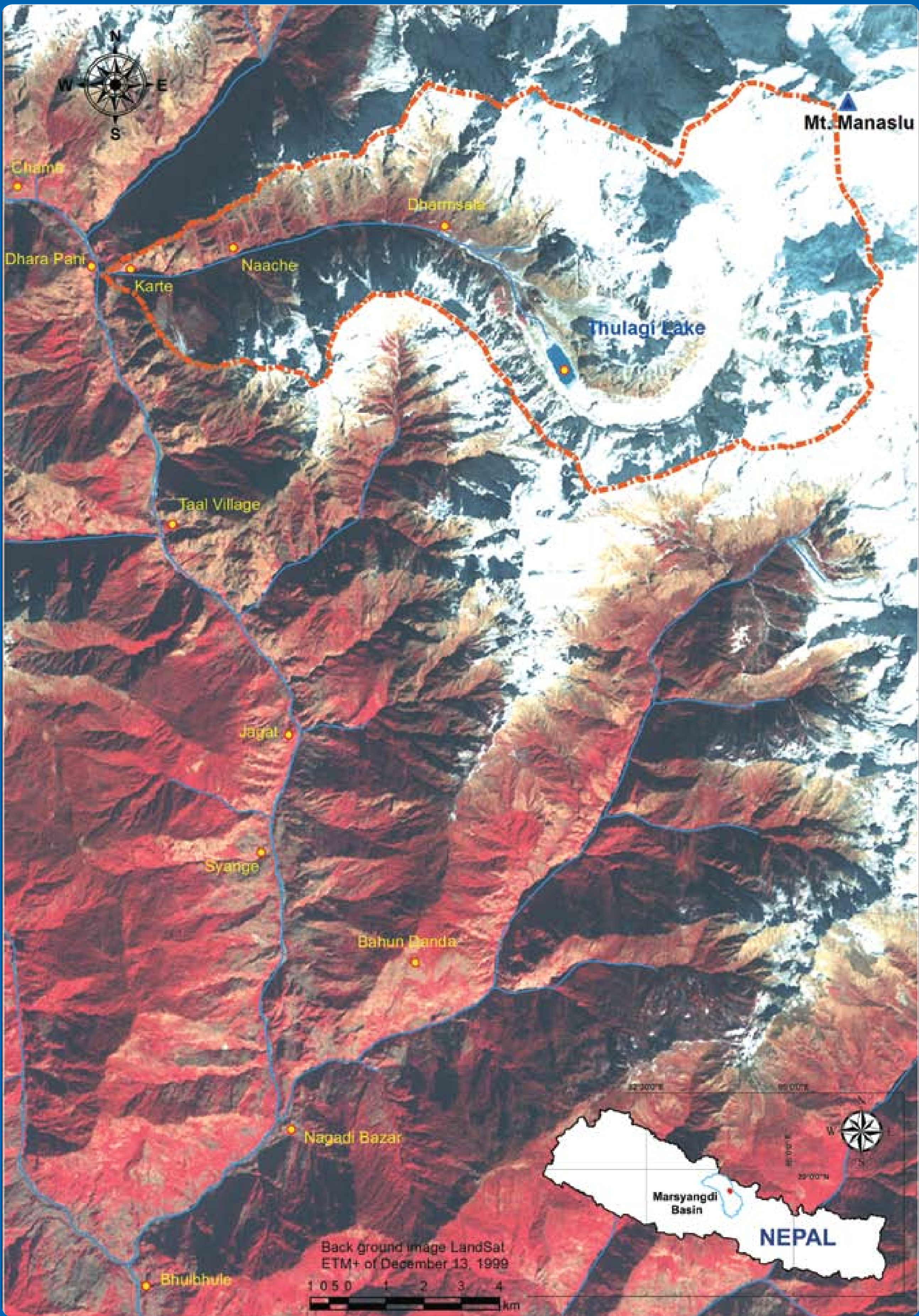


Figure 7.11: **Development of Thulagi Lake between 1960 and 2009 based on the Topographical Map of the Survey of India (1960), Nepal Survey Department (1995), Landsat TM (Nov 1990, Dec 1999), AVNIR-2 (Nov 2006 and Nov 2007), IKONOS-2 (Nov 2009), WECS Field Survey (1995) and ICIMOD (2009)**

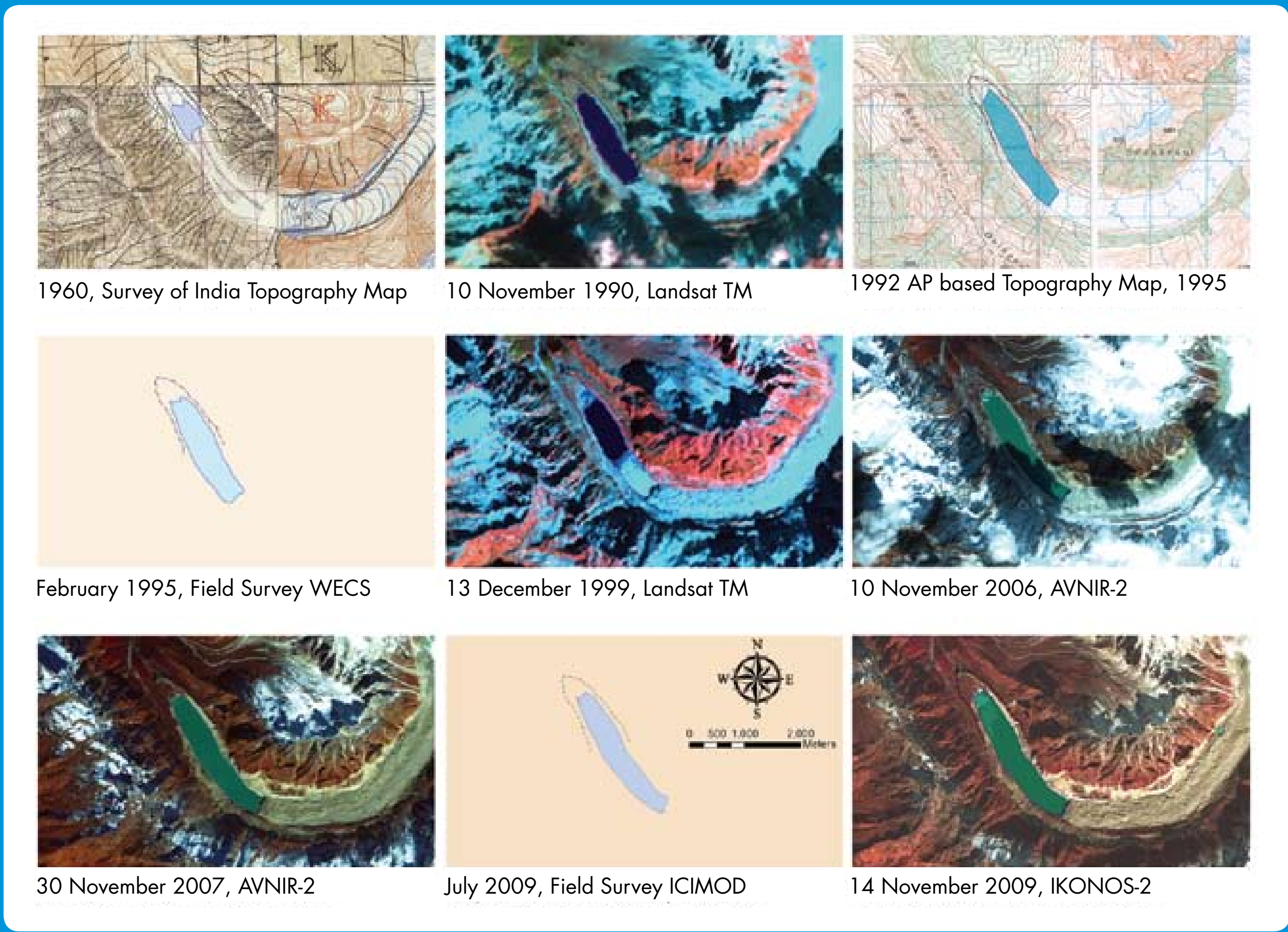
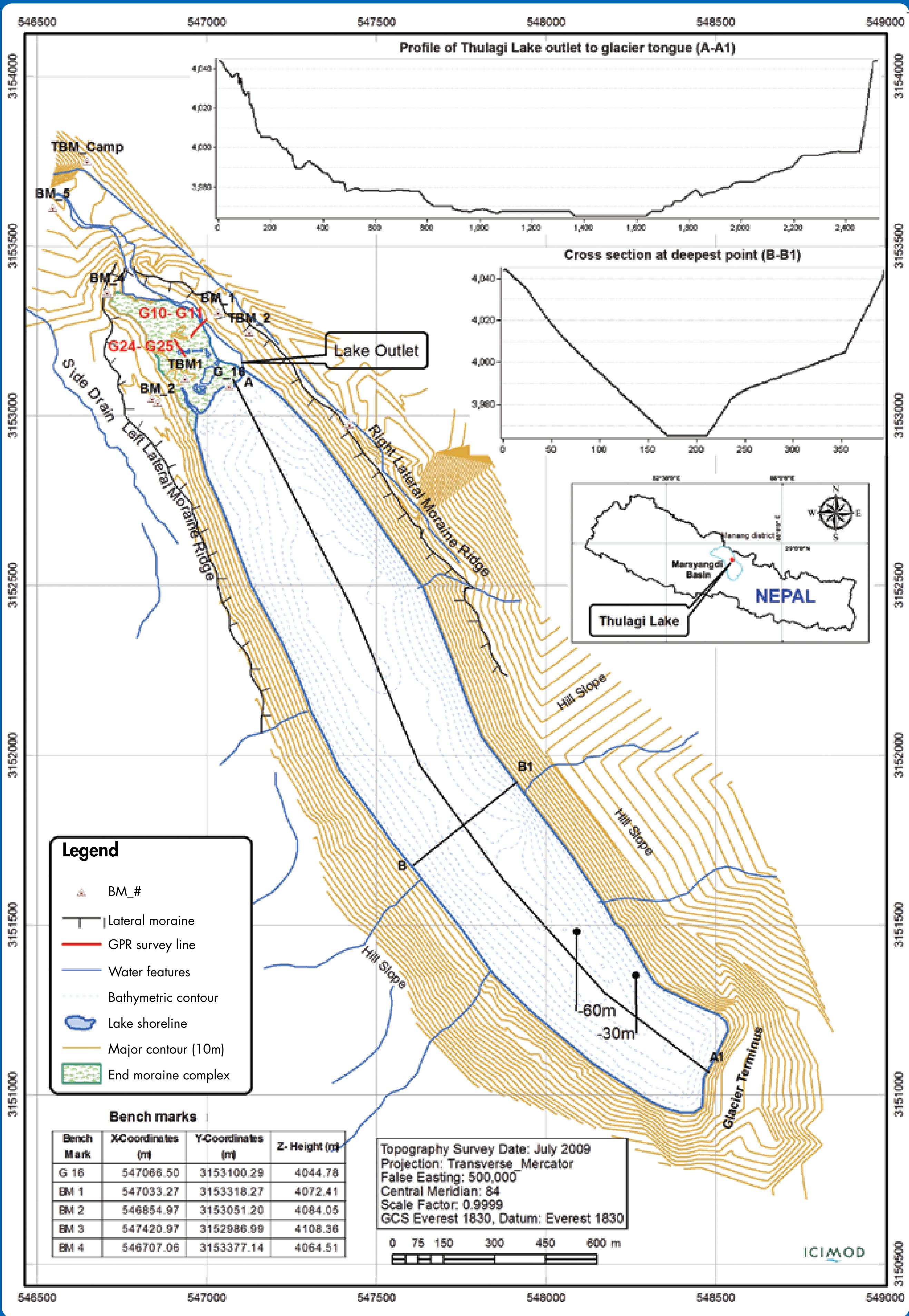


Figure 7.12: **Overview of Thulagi Glacier and glacial lake in 1992 photo (left) and 2009 December Quick Bird image (right); the red line shows the expanded area**

Figure 7.13: **Bathymetric and topographical map of Thulagi glacial lake showing the longitudinal profile and cross section along the deepest point. The GPR lines G24-25 and G10-11 show the location of buried ice.**



Bench marks

Bench Mark	X-Coordinates (m)	Y-Coordinates (m)	Z- Height (m)
G 16	547066.50	3153100.29	4044.78
BM 1	547033.27	3153318.27	4072.41
BM 2	546854.97	3153051.20	4084.05
BM 3	547420.97	3152986.99	4108.36
BM 4	546707.06	3153377.14	4064.51

Bathymetric investigation

Bathymetric survey data for Thulagi Lake were collected by traversing the surface in an inflatable boat with an outboard motor. Figure 7.13 shows the bathymetric and topographic map of Thulagi Lake together with the longitudinal profile and a cross-section at the deepest point. The volume was calculated to be 35.3 x10^6 cu.m, an increase from 31.75 x10^6 cu.m in 1995.

Comparison of benchmarks from previous field surveys by WECS (1995 c), DHM (1997), and NEA/DHM/BGR (2001) with the present field survey (2009) showed that the water level fell 2.18 m between 1996 and 2000 and a further 2.96 m between 2000 and 2009. This implies an average lowering rate of 0.3 to 0.5 m/yr. The lateral moraine walls are also lowering, but at a rate of about 0.1 m/yr: Benchmark 2 (BM 12 in the 2000 survey) on the left lateral moraine subsided by 1.27 m with a horizontal shift of 2.2 m between 2000 and 2009 (Field Data of WECS 1995c; DHM 1997; Field Data 2009). In other words, the moraine dam is sinking more slowly than the lake. The photographs show that between 2000 and 2009, both the lateral and the end moraines subsided and that the outlet channel shifted towards the right lateral moraine (Figure 7.14).

Hydrometeorology

There are no long-term meteorological data available for Thulagi Lake. The nearest meteorological station is located at Dharapani some 2000 m below Thulagi and thus represents quite different climatic conditions. The catchment area of the lake is approximately 56 sq.km of which 55% is covered by ice. It is mainly fed by meltwater from the Thulagi Glacier as well as by other cross-drainage systems. The outlet has a well-developed channel and appears to be stable (Figure 7.15).

Discharge in July 2009 (during the monsoon season) was at a rate of 3 - 4.5 cumecs.

Figure 7.14: **Changes in the shoreline of Thulagi Lake between 1996 (above) and 13 July 2009 (below), show the flow has now shifted towards the right lateral moraine, there are linear subsidence features on the left and right lateral moraines**

Figure 7.15: **The steep Thulagi outlet flowing through a narrow valley, 17 July 2009**

The empirical relationship (rating equation) derived between the lake-water level and the discharge measured at the Dona Khola was:

$Q = \text{Exp}(2.996) \times (H\text{-}H_0)^{1.223}$

where Q is the discharge in cumecs, H is the final height (water-level gauge) in m, and H_0 is the initial height (water-level gauge) in m.

Geophysical investigation

An electric resistivity survey indicated the presence of dead ice in the southeastern part of the end moraine damming the lake. The debris-covered segment of the terminal moraine was reported to consist of a 100 m thick body of ice. The shallowest depth for dead ice was about 5- 8 m on the southeast side (DHM 1997; Hanisch et al. 1998; Pant and Reynolds 2000).

The GPR survey during the current field investigation showed that the end and lateral moraines of the lake were made up of coarse and very coarse unconsolidated sediments. A transitional layer exhibiting moist sandy characteristics was identified at a depth of 16.5-17 m below the ground surface towards the western part of the end moraine. At the left bank of the channel, this transitional layer was underlain by buried ice (G24-25 and G10-11 in Figure 7.13). The ice core identified at a depth of 5 - 8 m in the late nineties had melted down to at least 20 m below the surface by 2009. Since the GPR can only penetrate up to a depth of 20 m, the actual depth of the buried ice could not be investigated. The radarogram indicated that larger fractions of sediments are dominant at a depth of about 12-14 m below the surface, where voids are also present. The area of large size sediments is underlain by sediments of medium size.

Glacier observations

The lower part of Thulagi Glacier is covered by debris. Its length decreased from 7.05 km in 1958 (Topographic Survey Map of India, 1960) to 5.38 km in 1999 (Landsat ETM+ 1999) giving a retreat rate of about 40.7 m/yr. Its length has reduced further to 5.03 km by 2009 (ICIMOD Field Survey 2009), a retreat rate of 35.1 m/yr. The glacier exhibits numerous transverse and longitudinal crevasses and collapse features. The collapse features are thought to be related to the rapid melting of the glacier tongue (through strong solar radiation) and its very slow movement. Several ice planes have developed on the lower portion of the ablation area due to longitudinal and transverse creep. There are ice cliffs (about 40 m high) at the glacier terminus and every so often ice calves and falls into the lake (Figure 7.16). The left lateral moraine closer to the glacier terminus contains much loose debris which falls into the lake. Rapid melting is causing the glacier to thin.

Discussion

Thulagi Glacier is a long, debris-covered glacier with a 40 m high terminal cliff. Even though ice calving is a regular phenomena, the surge that these calvings could produce are not deemed sufficiently large to trigger a GLOF event by the surge waves observed during the field study. Temporary blockage of the lake outlet by freezing water and snow barriers, or lake ice debris, appears unlikely, as indicated by the uninterrupted flow of the lake even during winter when the lake surface freezes. Lake drainage continues despite an average ice thickness of 0.4 m, as indicated by bore holes made through the ice during earlier bathymetric observations (WECS 1995c).

The peak monsoon flow from the Thulagi Lake is easily carried by its outlet channel. Regular monitoring is needed, however, to check for exceptional drainage input as discharge and debris from the side valleys, as well as to detect seepage flow and any undermining of the moraine dam.

Meteorological observations are needed to detect both extreme climatic events and annual variations. This could be accomplished by installing an automatic weather system (AWS) where data could be retrieved regularly, recorded, and published for public use.

Figure 7.16: **The Thulagi Glacier terminus in contact with the lake, the glacier tongue is about 40 m high above the water surface and exhibits snow stratigraphy (circle), 22 July 2009**

Summary of the Field Investigations

The key findings of the field investigations of the three lakes relate to the following issues: stability of the moraine dams; lake-storage volumes; GLOF triggering factors; hydrometeorological influences; potential GLOF hazard level; and monitoring, mitigation, and early warning systems.

Stability of the moraine dams

The elevation of Thulagi Lake is almost 1,000 m lower than that of Imja Tsho, which is significant in terms of climate regime and local vegetation. Thulagi had vegetation cover even close to the glacier terminus and surrounding the lake, and trees were growing on the terminal moraine. The outlet channel cuts through the right lateral moraine and its banks are being undercut.

The clasts in the moraine varied widely from pebble to gravel-sized particles in all three lakes, but there were also boulders measuring hundreds of cubic metres. The terminal moraine of the Imja Tsho was hummocky with a profusion of cones, mounds and depressions, whereas the Thulagi moraine was vegetated. Imja Tsho had the largest number and highest density (number per unit area) of sink holes, and they also had the largest radius. Boulders had also created large voids. The end moraine complex of Thulagi Lake displayed numerous small sink holes.

The height of the lateral moraines above the lake surface increased from the lake outlets towards the glacier termini in all three lakes, varying from less than 15 to 30 m near the outlet, to 30 to 50 m towards the middle section of the lake, and 50 to 100 m towards the glacier termini. The inner slopes of the lateral moraines were steeper, highly active, and eroded towards the glacier termini, and less eroded with partial vegetation cover closer to the outlets; this was particularly noticeable at Thulagi Lake. The inside slopes of the lateral moraines were composed of two distinct segments at all three lakes: lower segments inclined at about 30-35° (the angle of repose), and the unstable upper segments inclined at up to 45- 50°. The outer slopes of the lateral moraines were hummocky but stable with comparatively gentler vegetated slopes further strengthened by spur-like push moraines. The outer slopes of the Imja Tsho moraines had comparatively sparse vegetation cover.

The height of the side valleys between lateral moraine and rock slope were not physically measured during the field survey, but they appear to be at a greater elevation than that of the lake surfaces. Thus more emphasis was placed on the condition of the end moraines. In addition, the right lateral moraines of Thulagi Lake and Tsho Rolpa are in contact with bedrock towards the glacier termini. Overall, collapse of the lateral moraines is unlikely, but the lower sections could be more vulnerable to overtopping failures.

At all three lakes, the lateral moraines in contact with the glacier termini had buried ice with thermokarst features. In both Tsho Rolpa and Thulagi, the left lateral moraines also had thick loose debris, with more in Tsho Rolpa than in Thulagi. In both lakes, water enters laterally from the surface of the left lateral moraine.

The end moraine areas of all three lakes had linear cracks (Figure 7.17) that were more pronounced at the junction with the lateral moraines. The steep inner slopes are undercut by the surface currents in the lakes, and are also collapsing gradually as a result of ice melting within the moraine.

Lake growth

The physical characteristics of the three lakes as identified during the field surveys of 2009 are summarised in Table 7.1.

The development of all three lakes began at about the same time through amalgamation of small ponds. The more rapid initial growth of Tsho Rolpa resulted in it becoming the largest moraine-dammed lake in Nepal; Imja Tsho grew faster than Thulagi Lake (Figure 7.18). Tsho Rolpa has the largest storage volume and greatest lake depth (Figure 7.19). All three lakes are moraine-dammed and in contact with their associated glacier, and have thus mainly expanded towards their glacier terminus in parallel with glacial retreat and calving. Over the last decade, the expansion of Tsho Rolpa has been minimal, but Imja Tsho is expanding significantly and the glacier terminus is retreating. Its western section close to the end moraine is widening. The rate of expansion of Thulagi Lake is appreciable slower. The volume of Tsho Rolpa is increasing by an

Figure 7.17: **Contact of the lateral and end moraine complex with extensive linear features and sink holes at Thulagi Lake, 24 July 2009**

Table 7.1: **Comparison of the physical characteristics of the three lakes**

	Dam characteristics			Physical characteristics of the glacial lakes					Expansion rate per year[1]		
Lake	Height (m)	Free board (m)	Width (m)	Length (km)	Area (sq. km)	Storage volume (x10^6 cu.m)	Average depth (m)	Maximum depth (m)	Length (m)	Area (sq.km)	Volume x10^6 cu.m
Imja Tsho	31	10	567	2.03	1.01	35.5	35.1	96.5	42-47	0.0266	0.50
Tsho Rolpa	216	5	50	3.45	1.54	85.94	56.4	133.5	17-20	0.0129	0.26
Thulagi Lake	67	15	340	2.54	0.94	35.37	37.4	79.5	35-41	0.0115	0.53

Note: [1] Expansion rate per year' denotes values for Imja Tsho between 1992 (Yamada 1992) and 2009 (present study), for Tsho Rolpa between 1993/94 (WECS 1993, 1994) and 2009 (present study), and for Thulagi Lake between 1995 (WECS 1995c) and 2009 (present study)

average of 0.26 million cubic metres per year, and those of Thulagi and Imja by about 0.5 million cubic metres per year (Table 7.1). The water depth of all three lakes increases towards the glacier termini, but here the lateral moraines are 50-100 m in height and either in contact with bedrock or with debris or talus cover. Thus, the lateral hydrostatic pressure exerted by the greater depths are more or less counterbalanced by the lateral moraines, and the expansion of the lakes has not added any extra lateral pressure to the relatively weak moraine at the outlets.

There was no significant expansion of the lakes towards the end moraines apart from the widening of Imja Tsho: the outlet positions have remained more or less unchanged between the 1990s and 2009. The shoreline of Tsho Rolpa has undergone significant changes at the northwest and southeast of the end moraine and islands have submerged between 1993 and 2009. The Thulagi outlet channel had shifted towards the right lateral moraine and seepage and dried ponds were exposed. Changes in shorelines have also occurred in Imja Tsho, where thermokarst features were exposed at several locations.

Figure 7.18: **Comparison of lake development from images, topographical maps, and field investigation data for the Imja Tsho, Tsho Rolpa, and Thulagi Lakes. Imja lake grew at a slower rate up to 2000 when the rate increased; the growth rate of Tsho Rolpa diminished substantially after mitigation in 2000**

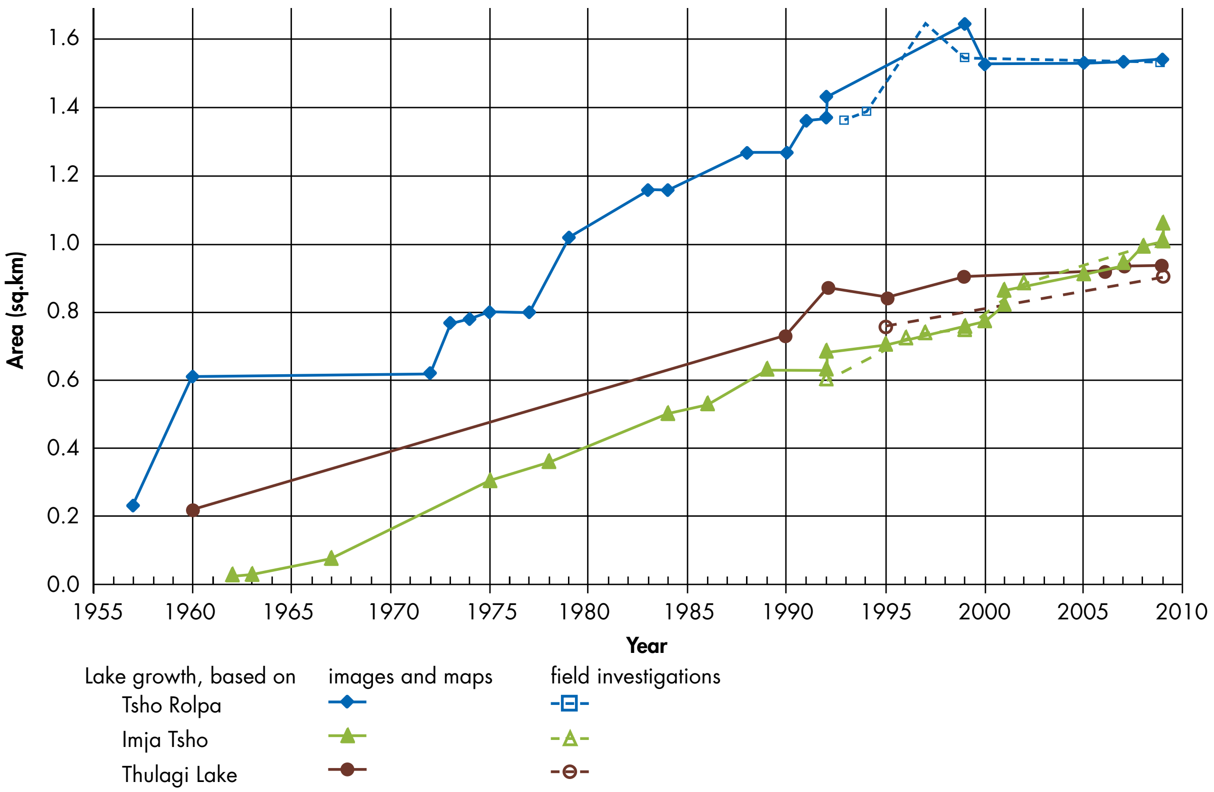
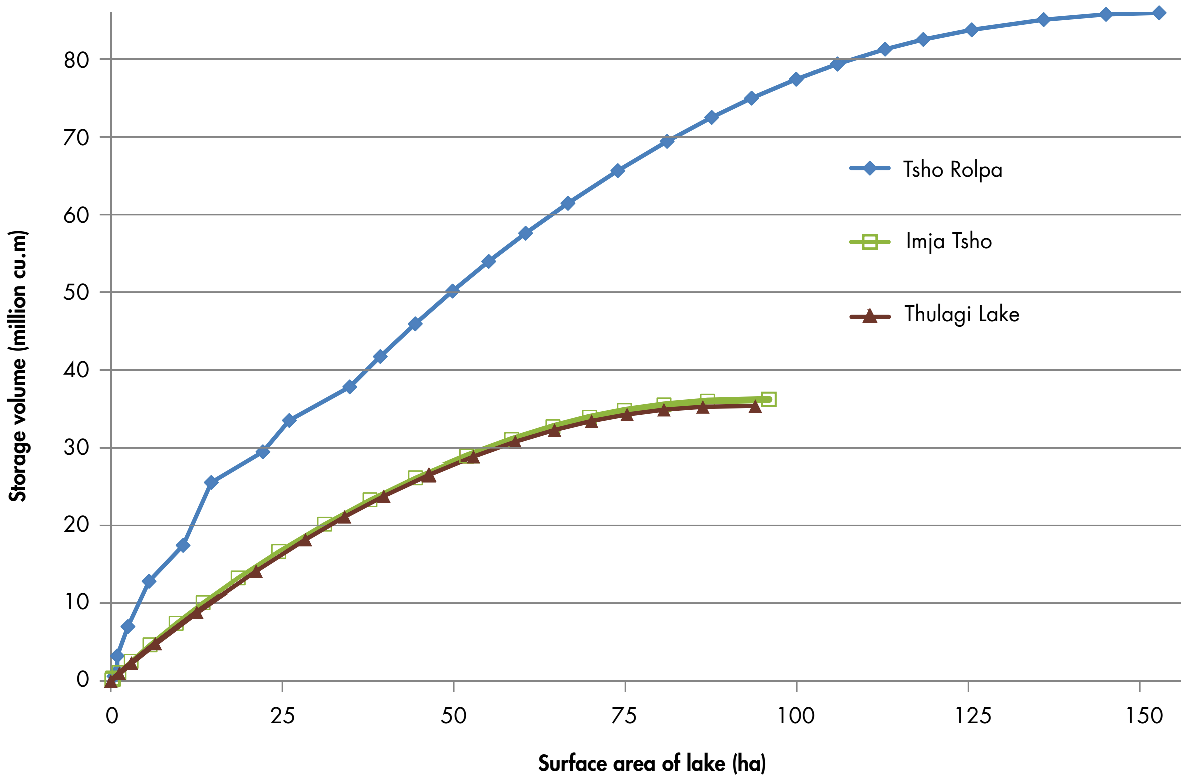


Figure 7.19: **The relationship of volume and depth for the Tsho Rolpa, Thulagi, and Imja lakes.**



GLOF triggers

The ablation areas of the Tsho Rolpa, Thulagi, and Imja glaciers were covered by debris derived mainly from the slopes above. The Imja and Thulagi glaciers have several transverse crevasses (Figures 7.5 and 7.16) and collapse features; they are calving into the lakes, although the collapsing masses of ice are not large enough to generate dangerous displacement waves. In the case of Tsho Rolpa, three hanging glaciers high above on Mt Tsoboje should be monitored for signs of instability as they could potentially produce ice avalanches.

Extreme events such as heavy snowfall or very high temperatures could destabilise the lakes. Earthquakes could also affect moraine and lake stability, however assessment of the potential danger of glacial lake outburst as induced by earthquake tremor is most likely beyond current competence.

Hydrometeorological influences

Hydrometeorological factors such as air temperature, humidity, radiation, wind speed, wind direction, and precipitation influence glacial melt, discharge into the lakes, and melting of buried ice. Because there is no long-term data base or systematic monitoring, understanding of likely impacts is limited.

All three lakes have an effective discharge capacity, hence there has been no significant rise in water levels. Undercutting of moraine slopes is not a substantial threat. In Thulagi Lake, even though there is some undercutting in the channel of the river at the foot of the right side of the end moraine, this effect is balanced out by the decrease in surface level of the lake.

The Trakarding, Thulagi, and Imja glaciers have temperate regimes (at 0°C), at least in their lower sections, and retreat has accelerated as a result of sub-glacial melt flow, sub-aqueous melting of ice (as shown by the lowering of the lake bottoms), and undercutting by water from the lake. Tsho Rolpa has a high concentration of suspended sediment load (Table 7.2).

Table 7.2: **Physical parameters of lake water of Imja Tsho, Tsho Rolpa and Thulagi Lake**

Parameters	Imja Tsho	Tsho Rolpa	Thulagi Lake
Date	May 2009	Sep 2009	July 2009
Conductivity (µS)	410	311	808
Surface water temperature (°C)	2	6.6	9.3
pH	-	6	6.5
Suspended solids (mg/l)	3.6	151.4	4.3

Potential GLOF hazard

The outlets are critical because all three lakes have low freeboards – 5, 10, and 15 m, for Tsho Rolpa, Imja, and Thulagi, respectively.

Tsho Rolpa's storage volume of 86 million cubic metres, dam height of 216 m, lowest freeboard (5 m), and narrow dam cushion, means there is more likelihood of a GLOF occurrence than from Thulagi Lake or Imja Tsho. Thulagi and Imja both have ca. 35 million cubic metres of storage, but considering their dam heights, widths, and freeboards, Imja Tsho has less likelihood of outburst than Thulagi Lake (Table 7.1). However there are many other parameters to be taken into consideration in making further assessment.

Although the lake level of Tsho Rolpa fell by three metres after the mitigation measures were put in place, there is still more likelihood of a GLOF occurring there than from the two other lakes. Tsho Rolpa is vulnerable to overtopping of low magnitude (about 5 m), thus, hanging glaciers, debris flow, or slides on a small scale pose a potential threat. Imja Tsho and Thulagi Lake have higher freeboards of more than 10 m and wider moraines (> 300 m).

All three lakes need to be monitored for seepages which can cause moraine dam failure by piping/undermining. Similarly, other key features including hydrometeorological conditions such as lake water level, excessive drainage, or extreme climatic conditions, and dam conditions such as subsidence or collapse of lateral and terminal moraines and moraine dam crest height and width (particularly for Tsho Rolpa) should also be monitored.

There is a further need to assess the influence of the surroundings, for example the impacts of hanging glaciers (Tsho Rolpa); debris flows/slides (Tsho Rolpa and Thulagi); and the condition of associated glaciers that may generate calving on a scale sufficient to cause a large surge wave. Variation amongst all of these features may influence GLOF hazard levels. Neotectonic activity or earthquake induced GLOF hazard is a possibility that should be considered, although prediction is beyond the current competence.

Overall the findings indicate that the immediate risk of a GLOF occurring is much lower than had been postulated for all three lakes; but many factors cannot be assessed, and catastrophic changes cannot be predicted. Thus there is an urgent need for more information as well as for regular monitoring and early warning systems.

An early warning system (EWS) was established before mitigation work on Tsho Rolpa began, although it is no longer operational. It should either be repaired or a new one installed (see chapter 10). EWS systems should also be installed for Imja Tsho and Thulagi Lake. Low cost EWSs (e.g., code division multiple access-CDMA) should be simple enough for operation and maintenance by the local communities. GLOF sensing and warning systems should give sufficient time for response. Awareness-raising in the local communities about the hazard and necessary response is essential. This recommendation was made by local, research, and government participants during the workshops and the field investigations.

Detailed risk assessment

The results of the field investigations were used in modelling experiments to determine more accurately the likelihood of a GLOF event occurring and the potential for downstream impacts. These detailed assessments are discussed in the following two chapters.

8 GLOF Modelling

Introduction

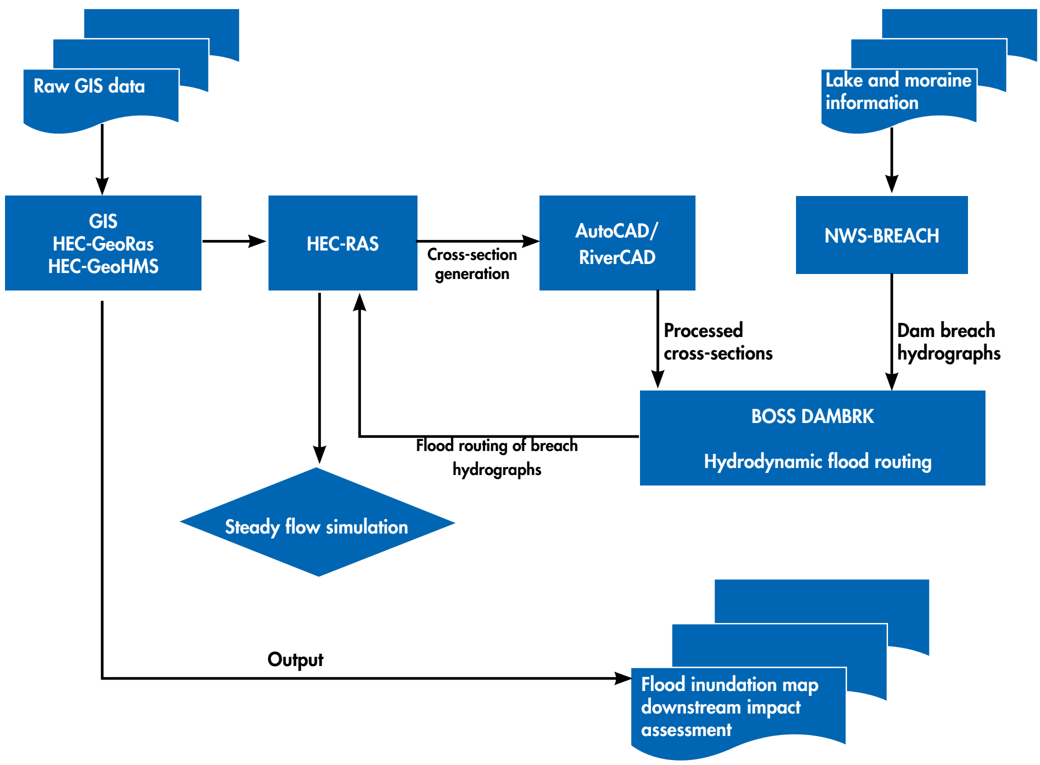
Detailed GLOF hazard and risk assessment is undertaken by simulating GLOF scenarios. Numerical hydrological modelling of the three high priority glacial lakes was carried out using data from the field investigations and from secondary data sources.

A breach model was used to simulate the failure of a dam. The breach hydrograph obtained with the model is simulated for flood routing in the valley downstream. The governing equations used for dam break models were the complete one-dimensional St. Venant equations for unsteady flow using internal boundary equations. Appropriate external boundary equations were used for the upstream and downstream ends of the routing. The hydrograph was specified as an input time series. Selection of breach parameters before a breach forms or in the absence of observations introduces a varying degree of uncertainty in the downstream flooding result of the dam break flood forecasting (DAMBRK) model. Errors in breach description and in the resulting peak outflow rate are damped out, however, as the flood wave advances.

Modelling Objective and Approach

The main objective of GLOF modelling was to simulate moraine dam failure of the high priority lakes and assess potential GLOF impacts downstream. The specific objectives were i) to develop a glacial lake breach model, ii) to develop a model of flood propagation in the valley downstream, iii) to develop a model of inundation in the river valley, iv) to forecast flood arrival time and velocity of flow, and v) to assess downstream GLOF impact. The study was in three stages: i) modelling outbursts; ii) modelling flood propagation downstream and flood mapping; and iii) downstream GLOF impact assessment. Figure 8.1 gives a schematic representation of the study method.

Figure 8.1: **Schematic representation of the methodology used for modelling GLOFs and assessing downstream impacts**



Sources of data

A hydrodynamic modelling approach was applied for GLOF simulation and vulnerability assessment. Topographic information about the study area determines the accuracy and reliability of the model. Spatial data such as a watershed boundary, digital elevation model (DEM) of the study area, drainage network, inline structures of rivers, land use/cover, settlements, infrastructure, and administrative boundaries were derived from the topographic maps of 1992 prepared by the Survey Department of Nepal, and satellite images.

The 2009 field survey provided data about the lakes including the surface area, maximum depth, and top and bottom elevations, and information about moraine dams including the inside/outside slope, dam length and width, unit weight of dam material, porosity, diameter of particles (d90, d50 and d30, at 90, 50, and 30% finer on the grain size distribution curve), and internal friction angle (ϕ). Manning's roughness coefficient n of the outer core of the dam was estimated. Socioeconomic information was obtained from field interviews.

A digital elevation model (DEM) of the study area was prepared; the Hec-GeoHMS modelling package was used to fill sinks and generate rivers for input into cross sections, flow lines were exported to AutoCAD and cross sections imported back to ArcView GIS. Data were exported to HecRAS for pre-processing. The top width and elevation were input into BOSS DAMBRK as breach definition, and lake and moraine dam parameters were input into NWS Breach for dam break analysis: breach hydrographs were generated based upon this (Figure 8.1). The breach hydrographs generated from NWS Breach were routed to BOSS DAMBRK for hydrodynamic flood routing.

The computer applications used for modelling watershed boundaries, river flow, and basin and river properties included ArcGIS/ArcView, HEC-GeoHMS; HEC-HMS; HEC-GeoRAS was used to acquire geometric data sets from the digital terrain model; and NWS-BREACH, BOSS DAMBRK, HECRAS, and AutoCAD/RiverCAD were used for GLOF modelling.

Input Parameters for the Dam-breach Model

The physical parameters of dams derived from field investigations and other sources were used to simulate breaching. The dam geometry and properties of dam material are given in Table 8.1.

Table 8.1: **Geometrical and dam material properties of Tsho Rolpa, Thulagi Lake, and Imja Tsho**

S. No.	Parameters	Unit	Tsho Rolpa	Thulagi Lake	Imja Tsho
1	Lake surface area	sq.km	1.53	0.94	1.01
2	Lake maximum depth	metre (m)	133.5	79.5	96.50
3	Dam top elevation	metre (masl)	4546	4044	5010
4	Dam bottom elevation	metre (masl)	4526	4024	4990
5	Dam inside slope	1:z	1:4	1:4.5	1:2
6	Dam outside slope	1:z	1:3	1:5	1:4
7	Dam crest width	metre (m)	50	20	50
8	Dam crest length	metre (m)	315	305	275
9	Diameter of 90% finer particle (d_{90})	millimetre (mm)	300-600	200-400	800
10	Diameter of 50% finer particle (d_{50})	millimetre (mm)	10# (5-15)	20# (30-60)	20#(10-30)
11	Diameter of 30% finer particle (d_{30})	millimetre (mm)	1-4	1-4	2
12	d_{90}/d_{30}		225#	150#	400#
13	Unit weight (γ)	kN/m^3	18# (17-20)	18# (17-20)	18
14	Porosity	%	30# (25-35)	30# (25-35)	30
15	Internal friction angle (Ø)	degree	35# (30-40)	35# (30-40)	38
16	Cohesiveness (c)	kN/m^3	0	0	0

= value adopted in breach model

Modelling Results

Dam-breach analysis and flood simulation

The NWS breach model was used for numerical estimation of breaching times and possible breach peak floods from the three lakes. More than 20 outburst scenarios for each lake were modelled in NWS-BREACH to test the sensitivity of the input parameters and their influence on results.

The breach height for all three lakes was derived as 20 m with breaching times of 0.62, 0.92, and 2.69 hours and peak flows at the time of flow as 7,242; 4,750; and 5,817 cumecs for Tsho Rolpa, Thulagi Lake, and Imja Tsho respectively (Figures 8.2 a, b, and c).

Flood routing

The outburst hydrographs of NWS-BREACH were used in DAMBRK for one-dimensional hydrodynamic flood routing for all three lakes. The potential flood stage, flood wave travel time, time to peak flood stage, and corresponding water surface elevations in downstream areas were calculated. The maximum flow, time to reach maximum flow, and high flood depth at various locations are given in Figures 8.3a, b, c for Tsho Rolpa, Thulagi Lake, and Imja Tsho respectively.

Beding, Suri Dovan, Lamatar, Khimti, and Rajgaun located at 9.6, 40.8, 75.5, 82, and 99.7 km from the Tsho Rolpa outlet, can expect flood arrival times of 0.79, 1.48, 2.76, 3.83, and 5.76 hours, respectively.

Dharapani, Tal, and Nayabasti located at 13.5, 19.2, and 94.1 km from Thulagi Lake outlet, can expect flood arrival times of 0.99, 1.17, and 5.40 hours, respectively.

Dingboche, Pangboche, Benkar, Ghat, and Rabuwa located at 7.97, 15.72, 29.18, 37.34, and 100.2 km from the Imja Tsho outlet, can expect flood arrival times of 3.124, 3.39, 3.8, 4.2, and 7.44 hours, respectively. Because of the wide crest width of Imja moraine dam, breaching takes about three hours as obtained from the NWS breach model; the data about the flood reaching downstream corresponds to the time breaching commences. The highest amount of discharge recorded by the Department of Hydrology and Meteorology, Nepal, at Busti near Nayapul is 2,130 cumecs. (gauge height 7.12 metres) on the 17th August 1998. It is estimated that a discharge caused by a 20 m dam breach in Tsho Rolpa would be about 2,929 cumecs just below Busti; which does not include sediment load or tributary flow data.

Figure 8.2: **Breach hydrograph of a potential breach**

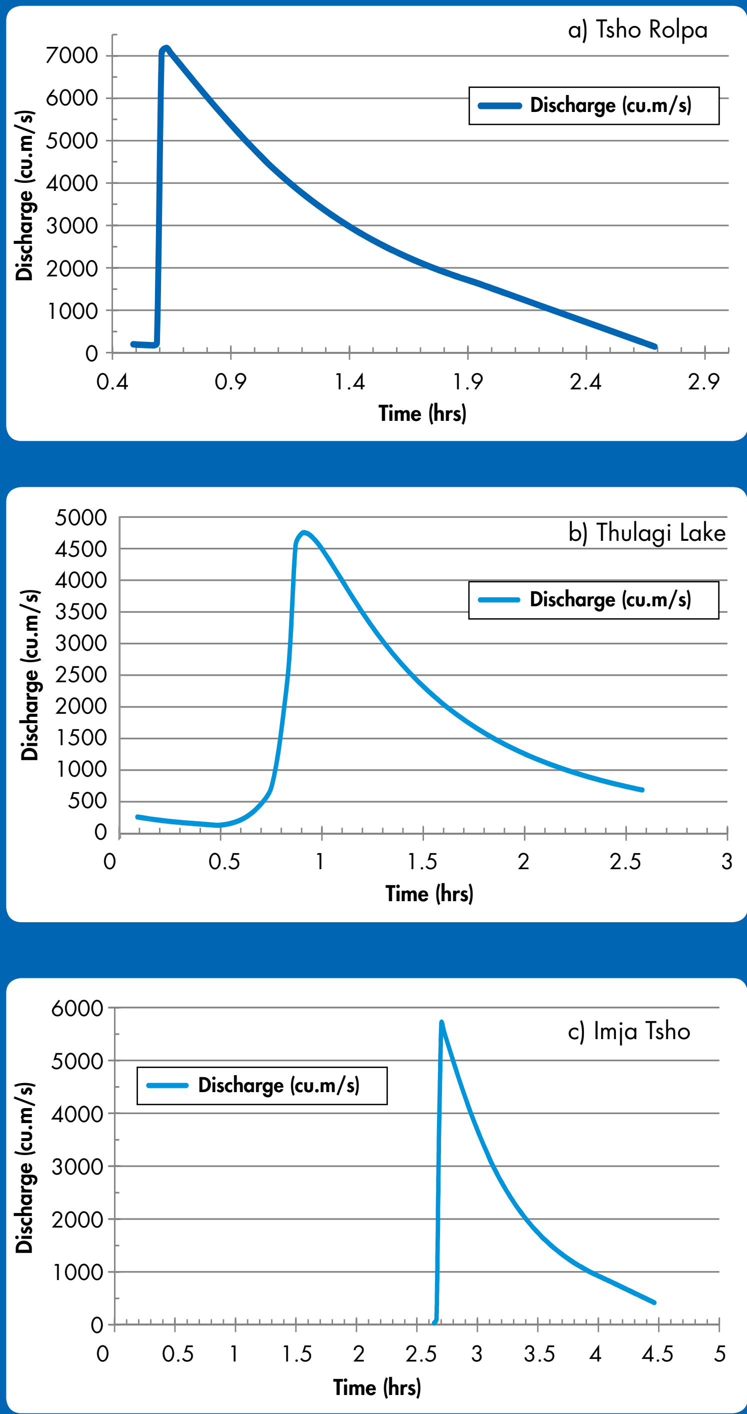
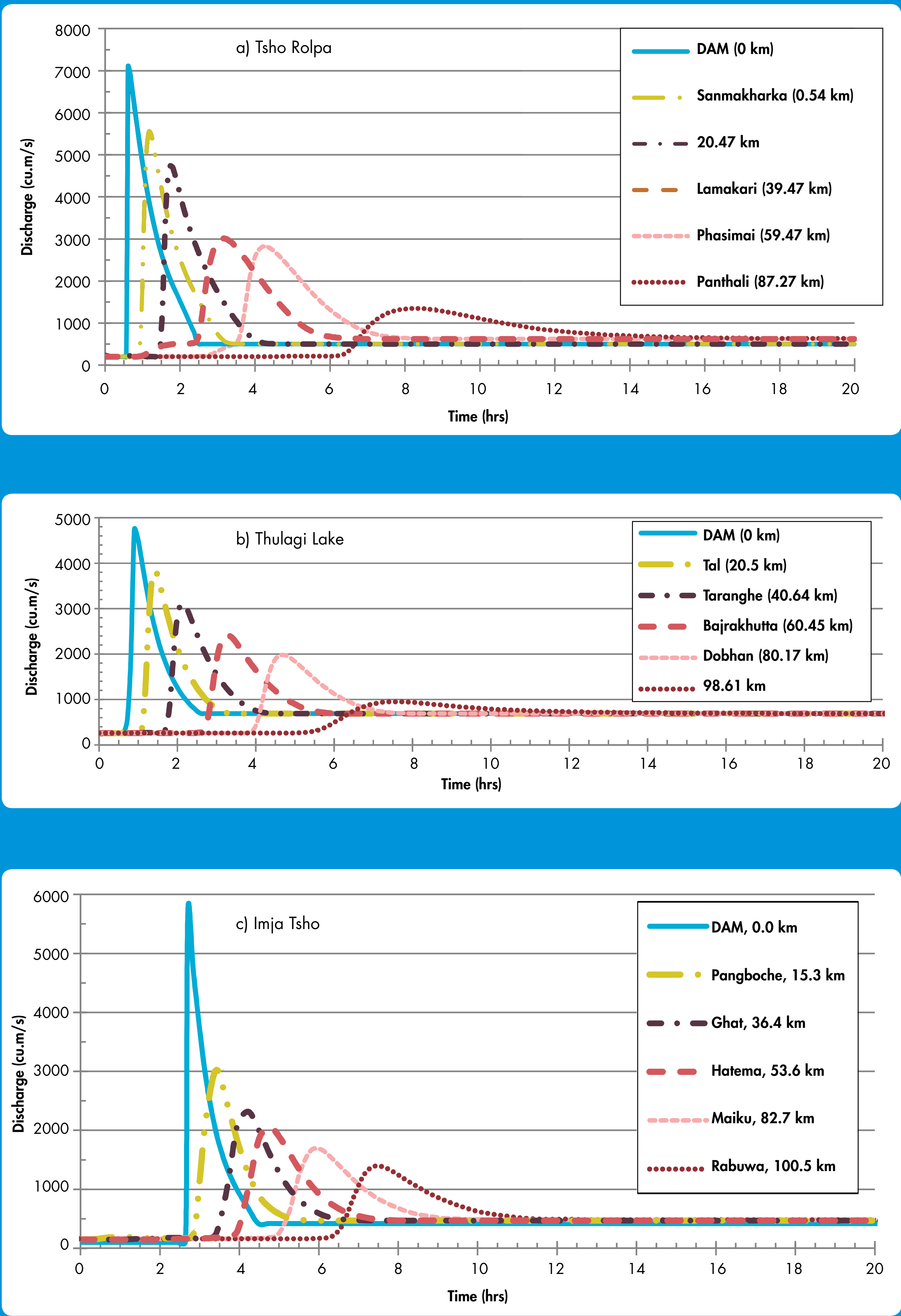


Figure 8.3: **Flood attenuation at various downstream locations**



Peak flow estimation and flood height

Flood routing along the valleys downstream differs among the lakes. Tsho Rolpa's peak flood decreases sharply in stretches, in the initial flow from the dam up to 10 km, then at 40-60 and 90-100 km. Apart from a flat stretch of 60-90 km, the stretches are moderately sharp (Figure 8.4a). Sanmakharka, Beding, Rikhu, Syalu, Suri Dovan, Nayapul, Jujar, and Rajgaun would experience flood heights of more than 10 m.

Flood routing for Thulagi Lake had a systematically decreasing trend in the peak flow with a gradual decrease as it proceeded downstream (Figure 8.4b). Dharapani, Tal, Sattle, Lampata, Dadabagar, Belghari, Naubise, Botgaun, and Nayabasti would receive a flood height of more than 10 m. Tal village located a few metres above the river would be seriously affected as the flood depth above the normal flow depth would be over 7m and all the settlements and land would be damaged.

The peak flood from Imja Tsho decreases sharply within the initial 10 km stretch, with a further gradual decrease beyond 20 km (Figure 8.4c). The potential flood height is less than those of Tsho Rolpa and Thulagi as heights are less than 10 m throughout the valley, even though the peak flood is higher than that of Thulagi Lake. Dingboche, Orse, Ghat, Bupsa, Lap, Phapare, and Kuwapani would receive moderate impacts.

Flood Inundation Maps and Downstream Impacts

Peak discharge and flood heights were calculated with numerical models on the basis of the GLOF modelling to simulate GLOF impacts downstream. Beyond 50 km, the initial peak flood is more or less halved. The areas impacted by either high peak flood or high flood levels were classified as high risk zones, and areas with potentially substantial socioeconomic losses were mapped as highly vulnerable. The (flood) inundation maps were overlaid with the socioeconomic data to assess GLOF vulnerability (Figures 8.5, 8.6, and 8.7).

Land exposed to a potential GLOFs

Possible landcover losses were estimated by overlaying the flood hazard maps on to landcover maps. The results are summarised in Table 8.2.

An estimated 833.2 ha up to about 100 kilometres downstream would be exposed to a GLOF from Tsho Rolpa: about 62% (515.0 ha) would be flooded along the course of the river, 38% would be agricultural land (169.8 ha), forests (68.6 ha), grassland (4.2 ha), shrubland (37.4 ha), and barren land (38.1 ha).

An estimated 1132.8 ha would be exposed to a GLOF from Thulagi Lake: about 73% (821.3 ha) would be flooded along the course of the river; 28% would be agricultural land (188.7 ha), forests (73.9 ha), grassland (33.3 ha), and barren land (15.6 ha).

An estimated 1009 ha would be exposed to a GLOF from Imja Tsho: about 56% (567.0 ha) would be flooded along the course of the river and 44% would be agricultural land (87.6 ha), forest (206.9 ha), grassland (54.1 ha), shrubland (24.1 ha), and barren land (35.8 ha).

Table 8.2: **Land-cover types exposed to potential GLOF risks from the three lakes up to 100 km downstream**

S. No.	Land-cover type*	Tsho Rolpa		Thulagi Lake		Imja Tsho	
		Area (ha)	%	Area (ha)	%	Area (ha)	%
1	Agricultural land	169.8	20.4	188.7	16.7	87.6	8.7
2	Forest	68.6	8.2	73.9	6.5	206.9	20.5
3	Shrubland	37.4	4.5	-	-	24.1	2.4
4	Grass	4.2	0.5	33.3	2.9	54.1	5.4
5	Barren land	38.1	4.6	15.6	1.4	35.8	3.5
6	River course	515.0	61.8	821.3	72.5	567.0	56.1
7	Other	-	-	-	-	34.4	3.4
	Total	**833.2**	**100**	**1132.8**	**100**	**1009.9**	**100**

* Source: ALOS Image, 2009

Figure 8.4: **Peak flood and flood height of the three lakes**

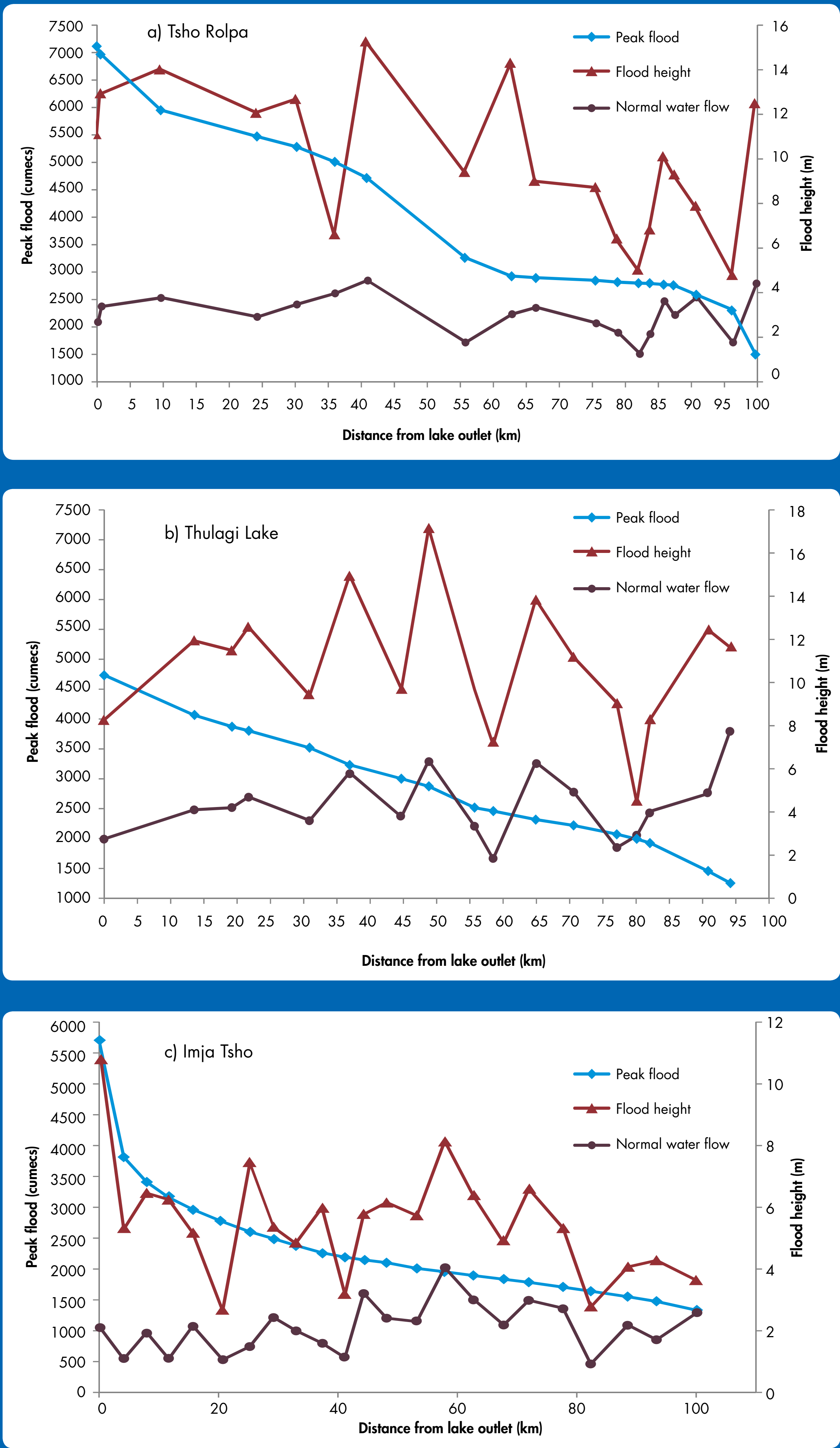


Figure 8.5: **Modelled flood inundation map along the Tama Koshi valley, downstream from Tsho Rolpa**

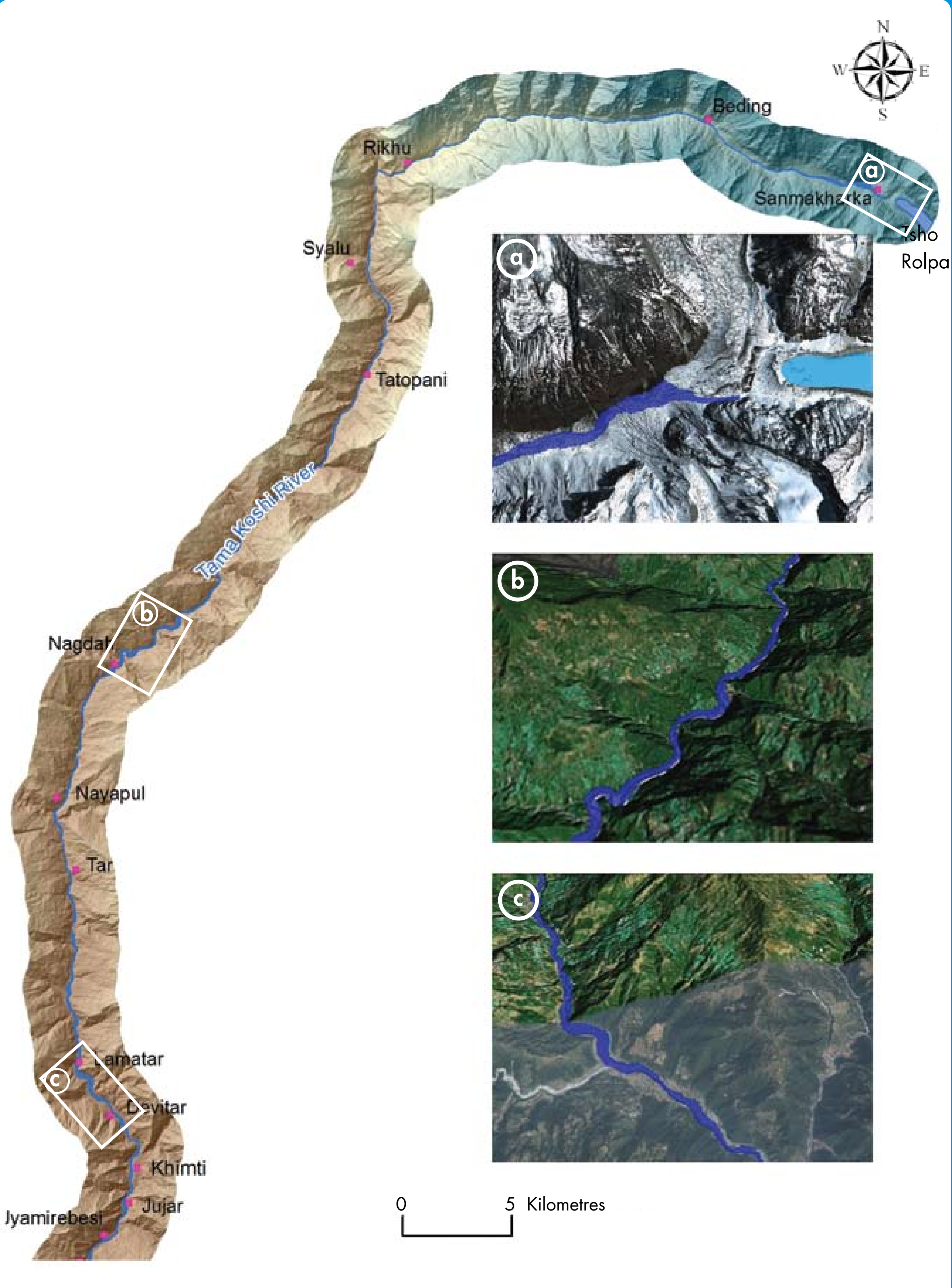


Figure 8.6: **Modelled flood inundation map along the Marsyangdi valley, downstream from Thulagi Lake**

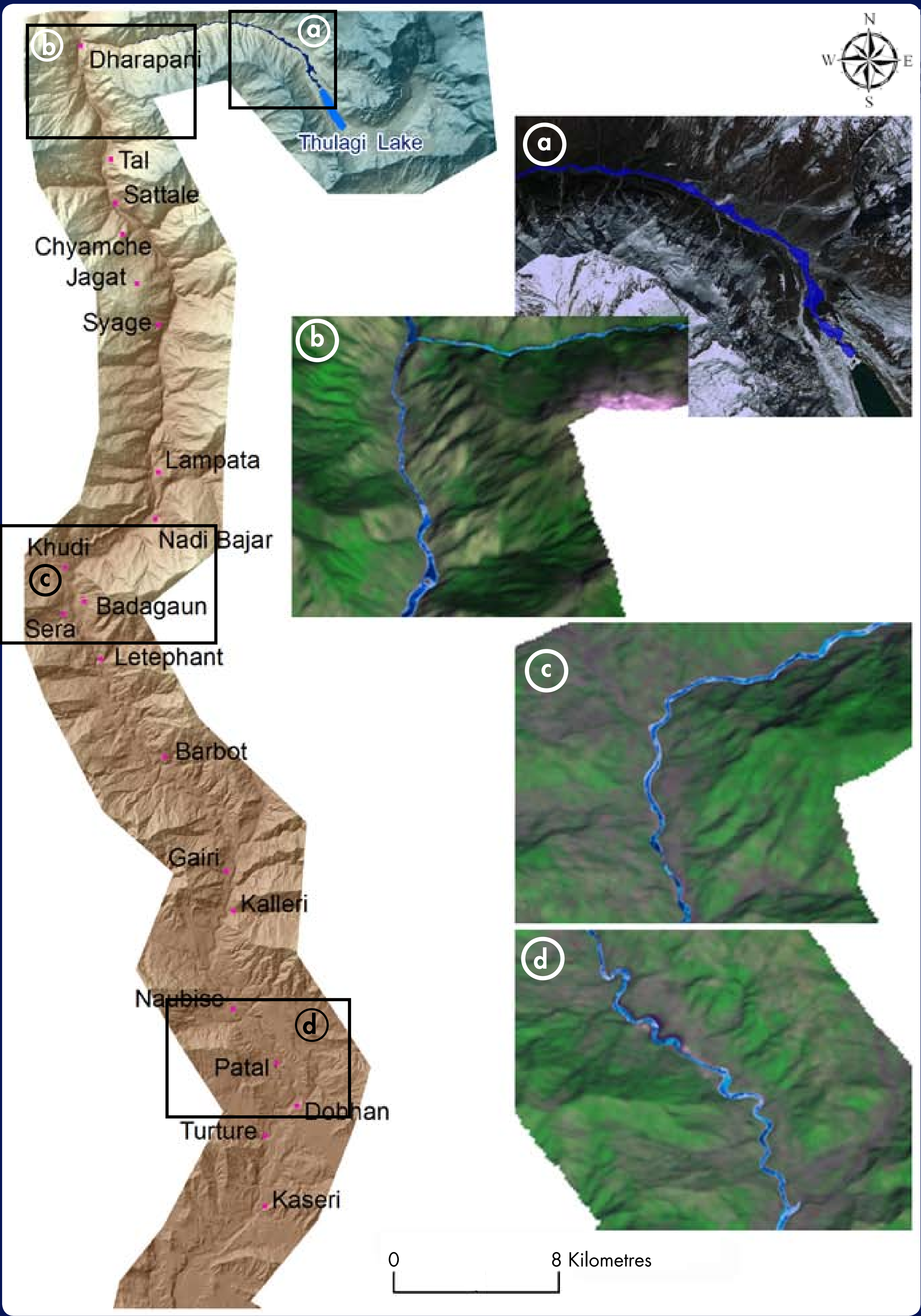
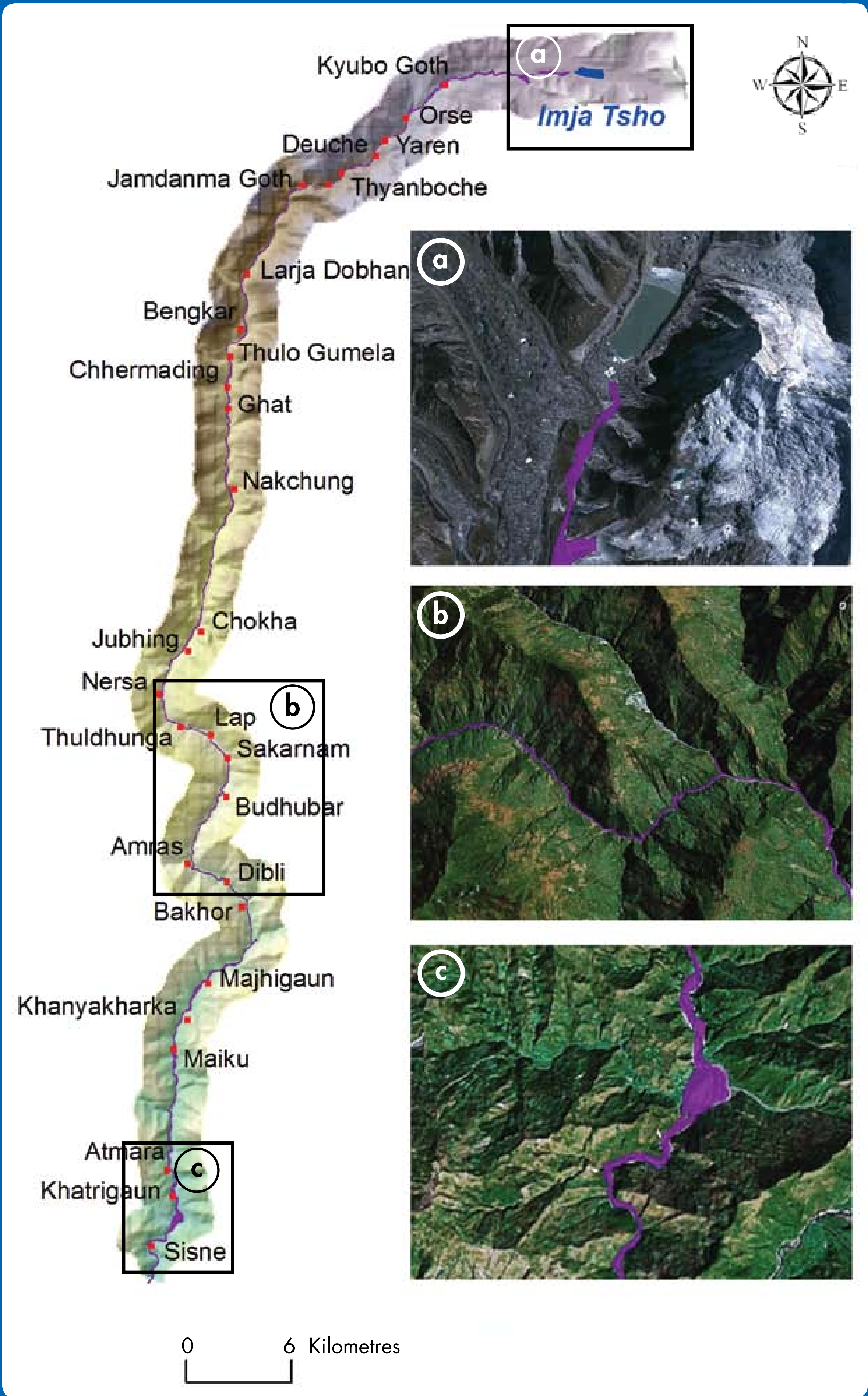


Figure 8.7: **Modelled flood inundation map along Dudh Koshi valley downstream of Imja Tsho**



Rolwaling river downstream of Tsho Rolpa from the end moraine showing the old (right) and new (left) outlet channels, 3 August 2009

9 Vulnerability Assessment

Introduction

To assess, and then mitigate, GLOF risks, it is essential first to estimate the actual potential for damage. This entails understanding both the hazard magnitude and the physical and socioeconomic vulnerability downstream. Determining the probability and magnitude of an event and assessing vulnerability and risk, are necessary for the preparation of response strategies. The probability of loss and /or damage can only be substantially reduced and resilience and /or restoration enhanced after a proper assessment of probable flood magnitude and impact. This chapter deals with vulnerability assessment.

There are two effects related to a GLOF hazard, a primary one characterised by inundation, erosion, and sedimentation up to the maximum calculated flood level, and a secondary one of slope failure that extends beyond the flood level depending upon the geology and materials in the river bed and its surroundings. Failures from past GLOFs were reported to extend up to 35 m above the river bed in areas where slopes were steep and unstable. Accordingly, the flood hazard zone is in two distinct parts: the 'modelled flood level', derived from numerical analysis of the hydrological model (dam-break model), and the 'maximum affected level', covering the area along the river bank up to 35 m above the river bed.

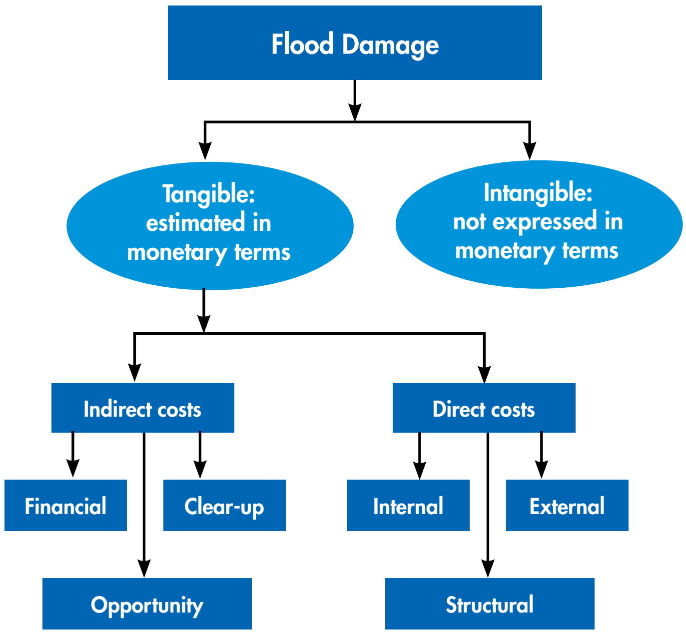
A vulnerability assessment was carried out for each of the three lakes and their downstream areas. The main objective was to obtain a systematic assessment based on past records, flood modelling, and interaction with local key stakeholders. The specific objective was to identify and quantify the elements exposed to risk, assess their vulnerability in terms of recovery and/or resilience, and identify and recommend strategies to increase the capacities of local people and institutions.

Economic Vulnerability

The economic elements exposed to GLOFs include lives, property, development projects and infrastructure, livelihood support systems such as tourism and trade, and environmental resources such as forest, pasture/ grazing land, and fisheries. The capacity of local people to cope with a natural disaster depends largely upon the diversity and quantity of household assets and access to information, technology, service infrastructure, and institutions; and this includes the degree of local participation.

We have defined damage in monetary terms based on the sum necessary to restore an area to its status quo ante. The damage caused by a GLOF event can be extensive and includes impacts on individuals and the community (Figure 9.1). Damage to property is the most common; the severity depends on three variables: the duration of the flood, the velocity of the flow, and the flooding level. Human lives can also be lost. Overall, the flood can cause varying degrees of distress and hardship.

Figure 9.1: **Types of flood damage**



Source: Guidance on the Assessment of Tangible Flood Damages, September 2002, Brisbane: The State of Queensland, Department of Natural Resources and Mines

Tangible damage can be estimated easily in monetary terms and can be grouped into direct and indirect damage. All physical assets affected are included in tangible damage. Direct damage (internal, external, and structural) usually accounts for most of the damage incurred. Indirect damage results from direct damage. For example, the breakdown of a section of a highway will either halt traffic or cause it to be diverted. The associated cost of this alternative is treated as indirect damage. Other examples of indirect damage could be closure of businesses or revenue or salary losses incurred from a breakdown in supplies, or costs incurred in ensuring people's health and wellbeing; in addition to which there will be the cost of repairing the direct damage.

Intangible damage refers to the negative impacts on social life which will extend well beyond the immediacy of the event. Important heritage sites can be lost and environmental quality (e.g., water quality) may deteriorate. Intangible damage reflects the social costs inflicted by an event which are not quantifiable, and refer to insecurity, distress, and depression, or inconvenience. Assessing intangible damage in monetary values is often not possible.

Hence only the tangible damage that can be expressed in monetary units was calculated when assessing the potential economic impact of a GLOF. The parameters used include the current purchase value of household assets – land, crops, livestock, and so on – and the cost of replacing infrastructure. In the case of roads and hydropower plants, the national average per unit cost is used; and the estimate is for the infrastructure as a whole as partial values are not easily derived, for example for hydropower projects. Secondary damage, such as the disruption of goods and services because of damage to infrastructure, is taken into consideration, but losses in tourism were not taken into consideration in this study because they are difficult to assess. However, an attempt was made to discuss potential GLOF risk to trade and tourism qualitatively during group discussions with the people who live in the basin.

Social Vulnerability

Social vulnerability assessments were derived from demographic and social characteristics such as the number of households, the population, and caste and/or ethnicity. The local capacity for GLOF risk management was assessed through household income (poverty) and livelihood support systems (sources of income, landholding size, and food sufficiency); literacy/education; skills; preparedness plans and practices such as land-use codes and standards; and social relations, institutions, and networking.

Methodology and Limitations

Primary and secondary sources of data were used for the study. Published and unpublished documents were collected and reviewed for secondary data. Primary data were collected in the field using a structured checklist. A key informant survey was held as well as group discussions. Transect walks and direct observation from the lakes and downstream areas were made. The information was entered onto topographic maps and recorded in field notes. Interviews took place in 12 areas around Thulagi Lake, 16 around Tsho Rolpa, and 23 in the Imja Tsho basin. Discussion group sizes ranged from 7 to 12.

The same methodology was adopted for all three lakes. Two different scenarios were used to identify GLOF-prone areas: one based on the flood level derived from the dam-break and hydrodynamic model, and the other based on a maximum height of 35 m from the river bed based on the maximum flood heights of past GLOF events. This height was used for development of a worst case scenario. Past events were considered when estimating the flood surge and extent of downstream damage, including the Nare GLOF in the Dudh Koshi valley in 1977; and the Zhangzangbo GLOF along the Bhote Koshi-Sun Koshi in 1981. Based on these events, the study carried out vulnerability and risk assessments for up to 100km downstream from the glacial lakes.

There were limitations in terms of identifying and qualifying elements at risk as well as socioeconomic and locational vulnerability. There was no detailed information available about existing infrastructure, such as the strength of the foundations or stress resistance, and hence physical vulnerability could not be assessed. The study had to rely heavily on information provided by the local people. There was also no record of internal damage as the field studies did not include detailed household surveys.

Estimated Exposure to Potential GLOF Risk

People and settlements

The downstream population in the adjoining village development committee (VDC) areas ranges from 96,767 for Imja, to 141,911 for Tsho Rolpa, and 165,068 for the Thulagi area. Of these, at the household level, the number of people likely to be affected by a potential GLOF varied from 953 in the modelled scenario to 3,808 in maximum scenario for Thulagi Lake; from 1,985 to 5,183 for Tsho Rolpa and from 5,784 to 7,762 for Imja Tsho. The remaining population could suffer a loss of environmental resources and service infrastructure. The maximum number who could be indirectly affected through infrastructural damage and loss of goods and services ranges from 501,773 for Imja, to 524,323 for Tsho Rolpa, and 2,044,145 for Thulagi (Table 9.1).

Table 9.1: **Population downstream within 100 km that could be affected**

Description	Imja Tsho	Tsho Rolpa	Thulagi
Population potentially directly affected due to loss of resources	96,767	141,911	165,068
Population potentially indirectly affected	501,773	524,323	2,044,145
Revenue earned in billion US$	8.98	2.4	2.2

Table 9.2 summarises the number of households and population likely to be directly affected and types and quantity of private property exposed to a potential GLOF. Information from the 1981 GLOF along the Bhote Koshi-Sun Koshi is also presented for comparison.

Table 9.2: **Summary of lives and property exposed to a potential GLOF risk**

Flood Scenario	Imja Tsho		Tsho Rolpa		Thulagi Lake		Bhote Koshi-Sun Koshi	
	Modelled flood	Maximum	Modelled flood	Maximum	Modelled flood	Maximum	GLOF in 1981	Maximum
Households								
No of households living inside flood-prone area	360	710	142	331	132	298	731	2,100
No of households having property inside flood-prone area	715	801	280	835	41	339	135	419
Total	**1,075**	**1,511**	**422**	**1,166**	**173**	**637**	**866**	**2,519**
Population								
No of people living inside flood-prone area	1,928	3,481	680	1,604	700	1,690	4,937	13,873
No of people having property inside flood-prone area	3,856	4,281	1,305	3,579	253	2,118	845	2,440
Total	**5,784**	**7,762**	**1,985**	**5,183**	**953**	**3,808**	**5,782**	**16,313**
Houses								
No of 'pakki' houses	59	238	85	200	77	195	248	586
No of 'kachchi' houses	386	570	60	130	48	103	483	1,527
Total	**445**	**808**	**145**	**330**	**125**	**298**	**731**	**2,113**
Land								
Area of khet land (ropani)	5,340	5,420	478	2,227	219	1,371	556	2,006
Area of bari land (ropani)	835	2,002	48	314	421	774	155	1,265
Total	**6,175**	**7,422**	**526**	**2,541**	**640**	**2,145**	**711**	**3,271**

Note: pakki = permanent, kachchi = temporary, khet = irrigated land, bari = rainfed land, ropani = unit of area (1 ropani = 0.0509 ha)

Exposure of property and infrastructure

GLOF events have downstream impacts at four different levels: individual household, VDC, district, and national. At the household level, impacts are either direct (from inundation) or secondary (e.g., from erosion or landslides). At the VDC level, people are affected by a loss of natural resources and service infrastructure. At the district level, damage to physical infrastructure disrupts the flow of goods and services, and at national level power supplies are disrupted because of damage to hydroelectricity projects, affecting populations living far beyond the GLOF area. The potential GLOF risk levels in the three glacial lakes studied were compared with the calculated GLOF impact on the Bhote Koshi Sun Koshi. The potential impacts were relatively higher for Imja than for Tsho Rolpa and Thulagi, and comparable to those of the Sun Koshi. This is because the Imja Tsho area lies within one of the top 10 tourist destinations in Nepal, whereas Tsho Rolpa (Rolwaling Conservation Area) and Thulagi (Annapurna Circuit) receive fewer tourists.

Monetary Value of the Elements Exposed

Table 9.3 summarises the monetary value of the elements exposed to a potential GLOF, and thus the potential cost of the damage, based on the modelling exercises. Again, the values from the Bhote Koshi-Sun Koshi GLOF are included for comparison. The revenue referred to is mainly from hydroelectricity.

Table 9.3: **Summary of monetary value of elements exposed to a potential GLOF risk (USD '000)**

Glacial lakes	Imja Tsho		Tsho Rolpa		Thulagi		Bhote Koshi-Sun Koshi	
Flood scenario	Modelled flood	Maximum	Modelled flood	Maximum	Modelled flood	Maximum	GLOF in 1981	1981 level+10m
Real estate	8,917	31,729	1,411	6,524	2,036	6685	15,889	40,606
Agricultural sector	932	1,680	117	330	234	519	246	996
Public infrastructure	2,037	2,084	319	1,928	335,784	339,469	98,845	109,446
Revenue	7	7	0	0	68,678	68,678	37,762	37,762
Total	**11,894**	**35,501**	**1,847**	**8,781**	**406,731**	**415,351**	**152,741**	**188,810**

The monetary value of elements exposed to a potential GLOF is quite high in the lower downstream areas in all three basins studied. This area accounts for 99% of the total amount for Tsho Rolpa and Thulagi and 51% for Imja Tsho according to the flood model. This can be explained by the increased amount of infrastructure downstream. An increase in GLOF level, however, would lead to increased damage in the headwater region.

Several proposals for hydroelectricity projects for the Marsyangdi river have been submitted to the Government of Nepal and they are likely to be commissioned in the near future. Should these projects be implemented, the risks to power supplies and revenue will be substantial: a total of USD 8.98 billion for the Imja Tsho, 2.4 billion for Tsho Rolpa, and 2.2 billion for Thulagi unless risks can be mitigated.

The flow of people and goods along routes to tourist destinations in the Dudh Koshi (Imja), Marsyangdi (Thulagi), and Rolwaling and Tama Koshi (Tsho Rolpa) varies considerably: more than 30,000 tourists visit the Dudh Koshi in the Khumbu region annually and 16,000 tourists visit the Dharapani area (near Thulagi). The number visiting the Tsho Rolpa area is unknown. The roads built for the Upper Tama Koshi hydroelectricity project in the Tama Koshi (Tsho Rolpa) and for the Manang area (Thulagi) have not only increased economic activities but also GLOF risks. Tourist facilities have been established along the river banks in high risk areas and, hence, the potential danger has grown.

The human capacity to deal with a GLOF event is poor. Farms are not large enough to provide sufficient food, and incomes are low. Indigenous ethnic groups account for more than 83% of the total families in the Imja Tsho area, 69% in the Tsho Rolpa area, and 90% in the Thulagi area. The Majhi and Thami, the main indigenous ethnic groups in the Tsho Rolpa area, are among the poorest people in Nepal and do not have the means to withstand and overcome a catastrophic natural disaster such as a GLOF. There are, of course, many other groups (including Tamang, Gurung, Rai, Magar, Sherpa, and Newar), but mountain groups as a whole are disadvantaged in Nepal with less access to education, resources, and national decision-making processes.

The exposures to the potential GLOF needed for the risk computation were calculated on the basis of information from focus group discussions, questionnaires, and transect surveys using replacement costs. These are preliminary estimates based upon existing infrastructure and not the potential economic benefit that could be harnessed in the future. The proposed large hydropower projects in the Tama Koshi basin would change the GLOF vulnerability of Tsho Rolpa in comparison to the other two areas. Thus estimations of vulnerability may change considerably over a short span of time depending upon the development activities in different basins. Changes in socioeconomic parameters will also influence future assessments.

The vulnerability of people living downstream from the three lakes differs in relation to the livelihoods and infrastructure characteristics of each area. Overall, the risk may change with passage of time and may also increase in the context of current atmospheric warming. In national terms, other lakes must also be considered. It is essential to develop an appropriate strategy and policy as well as short- and long-term action plans for GLOF risk management. The findings of the current study serve as a resource guide and provide materials for assessing GLOF hazards, socioeconomic vulnerability, and GLOF impacts downstream in Nepal. It is hoped that the findings will be useful in designing GLOF risk management and reduction strategies in Nepal, as well as throughout the Himalayan region.