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Dr. Marcelo Somos-Valenzuela	Prior field experience and bathymetric data
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Abbreviations and Acronyms

AASHTO: American Association of State Highway and Transportation Officials

ASTM : *American Society for Testing and Materials*

CBEWS: Community Based Early Warning System

CFGORRP: Community Based Flood & Glacial Lake Outburst Risk Reduction Project

DC : Direct Current

D-GPS : Differential Global Positioning System

DHM : Department of Hydrology and Meteorology

DNPWC: Department of National Park and Wildlife Conservation

ERT : Electrician Resistivity Tomography

GLOF : Glacial Lake Outburst Flood

GPR : Ground Penetration Radar

GSHAT : Global Seismic Hazard Assessment Program

HKH : Himalaya-Karakoram-Hindukush

HMGWP: High Mountain Glacier Watershed Program

IS : Indian Standard

KU : Kathmandu University

MBT : Main Boundary Thrust

MCT : Main Central Thrust

MFT : Main Frontal Thrust

MHz : Mega Hertz

MoHA : Ministry of Home Affairs

MW : Mega Watts

NPD : National Project Director

NPM : National Project Manager

PGA : Peak Ground Acceleration

PMU : Project Management Unit

RMR : Rock Mass Rating

RRCAP : Regional Resource Centre for Asia and the Pacific

STDS : South Tibetan Detachment

TAG : Technical Advisor Group

UNDP : United Nations Development Programme

UNEP : United Nations Environment Programme

UNU : United Nations University

USAID : United States AID

USCS : Unified Soil Classification System

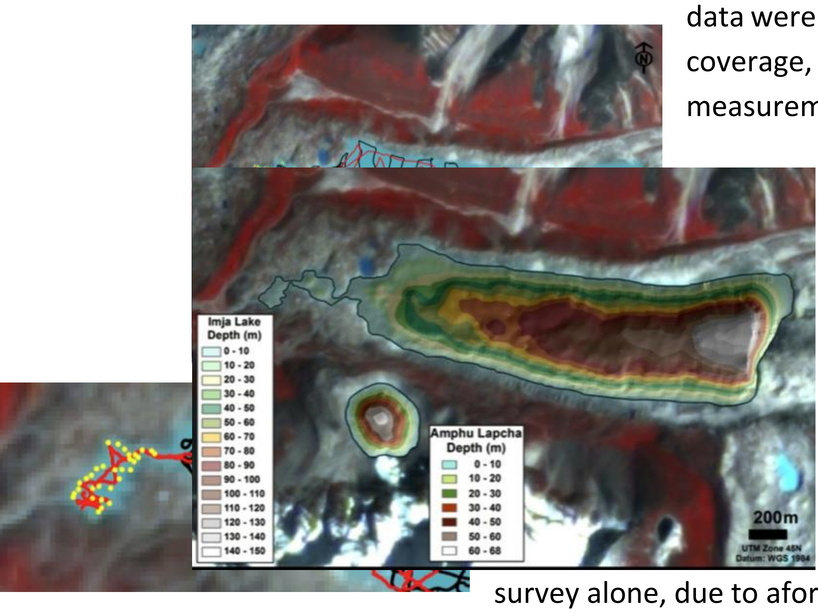
VDCs : Village Development Committees

WECS : Water and Energy Commission Secretariat

Executive Summary

The Community Based Flood and Glacial Lake Outburst Risk Reduction Project (CFGORRP) intends to reduce human and material losses from a potential Glacier Lake Outburst Flood (GLOF) from Imja Lake (5010 m) in Solukhumbu District by reducing the GLOF hazard risk in 27 downstream settlements by reducing Imja Lake's level by more than 3 m through construction of an open channel. As a part of the project the task of "Detailed Bathymetric and Hydrological/Glaciological Assessment required for Structural Design of lmja Lake Lowering" for input to technical design of the Lake lowering was awarded to the JV of ADMC Engineering (P.) Ltd. & DK Consult (P.) Ltd. The survey phase of the larger project was from 30 September to 31 December, 2014, after which the effort has moved to an engineering phase. This project is warranted, as our satellite-image-based time series of Imja Lake shows continued growth on a trend established since the early 1960s; furthermore, the damming end moraine is degrading.

At the survey phase of the project, field work for the bathymetric survey was completed between October 10 - 23, 2014 inclusive. Onsite work was preceded by a 5+ day acclimatization trek (October 5-10) from Lukla (~2840m) to Imja Lake site (~5000m). The bathymetric survey including echosoundings done from a USV (unpiloted surface vehicle) and from a kayak. The USV work was completed between October 11-13, 2014, when the boat's owner and primary operator, Umesh Haritashya was onsite. Most of the kayak bathymetric survey work was then undertaken. Data gaps remained from the USV-kayak echosounder surveys due to development of unseasonal lake ice, which hindered data acquisition in some parts of the lake and entirely prevented acquisitions in some other small but important areas. To fill the data gaps, additional depth measurements were made by plumb line through augured holes in lake ice to reach high-priority areas where previously we had been unable to obtain measurements or where a higher areal coverage was desired. The team also contacted Professor Daene McKinney and Marcelo Somos-Valenzuela, who had previously obtained a limited set of echo-soundings in 2012. These data were provided to us, thus improving data density and coverage, and were analyzed together with our new measurements.



The figures at left show the 2014 USV and kayak survey lines (black) and the 2012 survey lines (red) where valid data were obtained, and it also shows the locations of supplemental plumbline measurements (yellow dots) mainly in the lower pond on the end moraine. The combined datasets provided a higher density and wider areal coverage than was possible from our 2014 echosounding survey alone, due to aforementioned problems of unseasonal lake ice.

This report presents brief description of the field investigation and preliminary outcomes of the study. A bathymetric map of the lake obtained from the combined data is shown at left (superposed on a false-color satellite image). We have found that the lake attains greater depths (149.8 m) and has a greater volume (75 million cubic meters) than previously assessed by McKinney & Somos-Valenzuela (2014), who found a volume ~61.7 ±3.7 million cubic meters and maximum depth of 116.3 ±5.2m. The increase found in this study reflects the more thorough measurements we now have and an actual increase in lake area and mean depth. However, those two dimensional increases are not readily de-convolved, so we do not know the true rates of deepening and volume increase. Our satellite measurements show that the lake has continued an area growth trend established since the early 1960s. The lake deepens from the end moraine almost to the glacier's calving margin. Intra-valley bedrock basins and local up-valley deepening is a common phenomenon in glacier-sculpted valleys, particularly where multiple tributary glaciers coalesce, as in this locality. Comparison of our longitudinal depth profile with previous surveys suggests that much ice has melted recently on the eastern lake bottom.

We also assessed the depths of two small ponds that are growing along the outlet on the end moraine. The form and growth of these ponds are consistent with a thermokarstic development of the ice-cored moraine. The ponds add trivially to the total water volume of the system, and this will be true also if the ponds grow. However, these ponds' growth is of concern because they are progressively eroding the moraine dam's height and they are creating a shallow-water conduit over the end moraine along which a tsunami wave could surge. As the ponds grow, they will progressively narrow the end moraine so that less energy would be dissipated by any GLOF discharge, hence will make a large and rapid GLOF—triggered by any type of mechanism—more likely. Therefore, our new echo-sounding on the upper pond, the plumb-line data, and the prior echo-sounding survey by Somos-Valenzuela et al. are crucial to be analyzed together to fill in details for the ponds.

We have assessed seepage through the end moraine, which is happening but is not a large part of the system's present hydrology. Limited seepage may attest to the presence of impermeable massive glacier ice within the end moraine, consistent with findings by the electrical resistivity and ground penetrating radar thematic teams. Seepage is concerning because as buried dead ice melts, the seepage may increase and rapidly enlarge conduits.

We have summarized and partly quantified mechanisms by which the containment provided by the end moraine dam could be disrupted and generate a GLOF. High stream discharge due to extreme weather is not the most challenging engineering concern or greatest hazard concern. Most difficult for downstream communities are tsunami waves that could be produced by large mass transfers into the lake (e.g., giant rockfalls, ice avalanches or sturzstroms), large calving events, or sudden flotation of thick, massive ice thought to exist under parts of the lake. Presently, due to the presently configured topography of the mountains near the lake, very large mass movements are unlikely to collapse into the lake, but small tsunamis are likely due to

smaller moraine collapses or small ice avalanches. However, the probability of very large mass movement probably will change in the next couple decades as the lake lengthens and extends closer to the the areas's very high peaks. Presently, flotation of submerged ice might be the biggest potential cause of a large tsunami. However, this type of potential GLOF trigger is not well understood either by experience with other lakes or theoretically.

There are many potential types of GLOFs as defined by mechanism of release, volume, and duration (hence, peak discharge); not all carry a high hazard potential. The duration of water release is more crucial than total released volume. GLOFs elapsing over many hours or a day or two could create impressive floods but would not likely take out villages downstream from Imja Lake, but likely harm only people caught near/in the Imja Khola channel. The biggest threat and also the most difficult engineering challenge is specifically from "fast GLOFs" (not necessarily large in total released volume) that could be produced in minutes by (1) a large tsunami wave which could override the end moraine, or (2) sudden collapse of possible ice caverns or honeycomb structure in the end moraine. A substantial increase of freeboard and much more than 10 m lake lowering would be needed to substantially reduce the threat posed by "fast GLOFs." Open channel depths of 3 m and cross section of wetted perimeter of order 8 m^2 can protect against extreme rainfall events or other mechanisms that might produce "slow GLOFs" and would reduce the likelihood and potential magnitude of "fast GLOFs."

In support of the engineering design requirements, from 17-22 October 2014 we measured the discharge from Imja Lake. Discharge averaged 0.685 m^3/s and ranged between 0.529 and 0.920 m^3/s. These values compare to 2.61 m^3/s discharge measured at Dingboche on 15 Oct 2015. The ratio of average discharges from Imja to that at Dingboche is 0.262, which is similar to the ratio 0.28 of the basin areas draining to the two places. Our further analysis supports application of the area-scaling ratio 0.28 to the entire decade-long record of discharge at Dingboche to get a rough estimation of the daily, monthly, and annual hydrograph at Imja Lake, with due allowance for local perturbations. Use of the available records suggests that the long-term annual average discharge from Imja Lake is about 0.73 m^3/s, and the mean monthly discharges range from a low of 0.38 m^3/s (February) to a high of 1.45 m^3/s (August). The 10-year daily hydrographic record at Dingboche, with the 0.28 area scaling factor applied, extrapolates to a 100-year flood (1-day peak discharge) of 5.7 m^3/s at Imja Lake. With hypothetical addition of trasnient runoff from a microburst, runoff could attain 9.7 m^3/s.

Acknowledgements

We are grateful to the United Nations Development Programme (UNDP), Kathmandu for awarding the task of "Detailed Bathymetric and Hydrological/ Glaciological Assessment required for Structural Design of Imja Lake Lowering" for input to technical design of the Lake lowering to the JV of ADMC Engineering (P.) Ltd. & DK Consult (P.) Ltd., Kathmandu.

We would like to express our sincere gratitude to the management team of DHM specially the National Project Director (NPD), Director General (DG), Dr. Rishi Ram Sharma, CFGORRP/ DDHM, National Project Manager (NPM), Top Bahadur Khatri, CFGORRP, for their intense interest in this study as well as providing valuable suggestions that improved the quality of this study.

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Chapter One

1 INTRODUCTION

1.1. Issues relating to glacier lakes in Nepal

Himalayan glaciers form the largest body of ice outside the polar caps and are the source of water for the innumerable rivers that flow across the Indo-Gangetic plains. Himalayan glacial snowfields store about 12,000 km^3 of freshwater. About 15,000 Himalayan glaciers form a unique reservoir which supports perennial rivers such as the Indus, Ganga and Brahmaputra which, in turn, are the lifeline of millions of people in South Asian countries (Pakistan, Nepal, Bhutan, India and Bangladesh) (IPCC WGII AR4).

Glaciers are highly sensitive to climate change due to their relatively quick response. Climate cooling results in glacier advancement and warming leads to glacier retreat; so they are excellent indicators of climate change. Hence, recent glacial retreat and concomitant glacial lake formations/expansions in mountain areas serve as an example and infallible testimony of climate change. As glaciers retreat, lakes commonly form behind the newly exposed terminal moraine. The rapid accumulation of water in these lakes can lead to a sudden breach of the moraine dam. The resultant rapid discharge of huge amount of water and debris is known as a glacial lake outburst flood (GLOF). These GLOF events may result into catastrophic damage to the downstream areas. In the 2007 Intergovernmental Panel on Climate Change (IPCC) Working Group II Report (Cruz et al., 2007) it was mentioned that the Himalayan glaciers are receding faster than in other parts of the world. Some intermittent glaciological studies since 1970s revealed that Nepalese glaciers are showing this trend to some extent.

Temperature data collected from the mid-1970s from 49 hydro-meteorological stations of Nepal indicate that the average temperature between 1977 and 1994 increased at a rate of 0.06 °C per year (Shrestha et al. 1999 and Shrestha and Aryal 2011; Xu et al, 2007). The warming trends varied from 0.068 to 0.128°C/yr in most of the Middle Hills and Himalayan regions, while the Siwalik and Tarai regions show warming trends of less than 0.038°C/yr (Shrestha et al., 1999).

GLOFs occur relatively infrequently, but are a severe flood risk in the High Mountains. ICIMOD has identified over 1466 glacial lakes in Nepal (ICIMOD 2011). Most of these have been formed in response to warming temperatures during the second half of the 20th century (Yamada and Sharma 1993; Yamada 1998; ICIMOD, 2011), as a result of rapid glacier melting. Various studies indicate that the warming trend in the Himalaya region has been greater than the global average (ICIMOD, 2007).

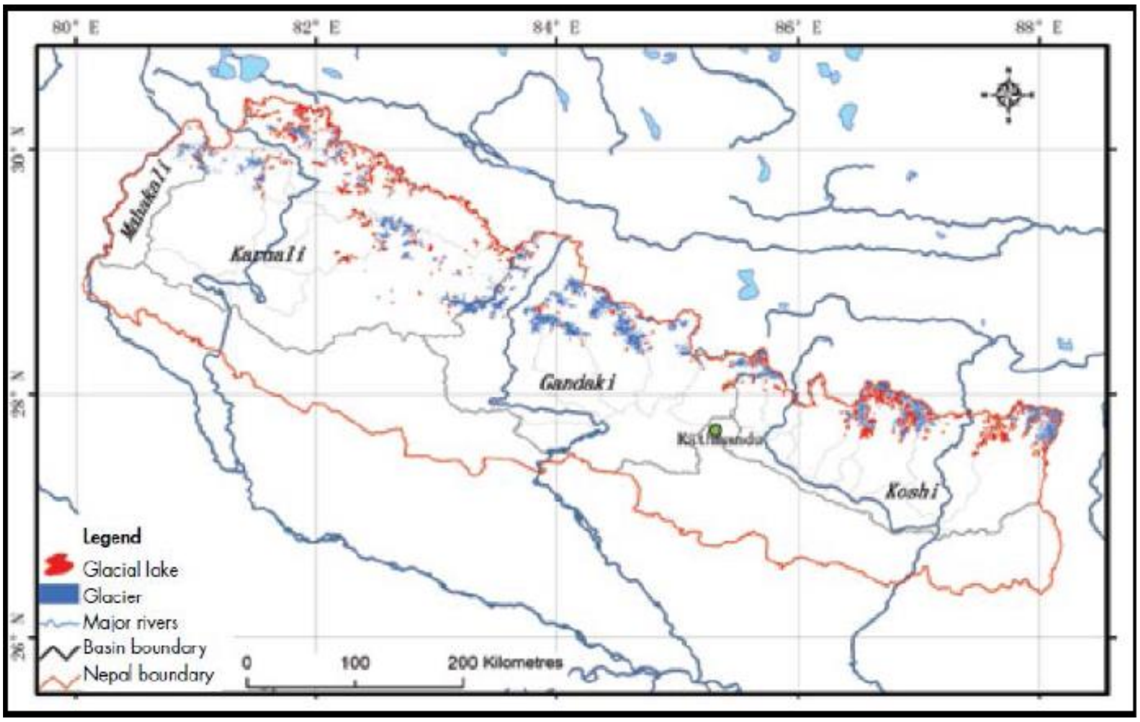


Figure 1.1. Distribution of Glacier lakes in Nepal Himalaya (Source ICIMOD 2011)

Studies have shown that the majority of present day large moraine dammed lakes did not exist before the 1950s. These lakes started forming in the mid 1950s to early 1960s, and in the 1970s they grew in a rather rapid manner (Watanabe et al 2009; Bajracharaya and Mool 2009). Most of the glacial lake outburst flood (GLOF) events recorded in this region happened in the last three decades or so. There have been suggestions that the GLOF frequency in this region has increased in recent decades (Ives et al., 2010). There are over 200 potentially dangerous glacial lakes in the HKH region: ICIMOD (2007) classified 10 to be very hazardous, which could burst out and cause flash floods. ICIMOD (2010) presented a renewed analysis and identified 21 lakes as posing exceptional risks. Under the observed and projected climate scenarios, it is very likely that the risk of GLOF events will increase in future because many glaciers are undergoing the type of thinning and slowing flow that spurs formation of new lakes.

The Dudh Koshi sub-basin of Nepal contains twelve potentially dangerous glacial lakes, among them Imja Lake is one of the fastest growing lake in Nepal. Because of the risk associated with Imja Lake, implementation of mitigation and safety measures is really essential. This situation, together with realization of increase of melt water stored in the Imja Glacial Lake in Solukhumbu district in Nepal, has prompted the Community based GLOF risk reduction project to lower down the lake water level by >3 m.

1.2. Imja Lake: Archetypical moraine-dammed glacier lake

Imja Glacial Lake is located in the eastern part of the Sagarmatha region in Solukhumbu district, Nepal. Lhotse Shar, Imja and Ampulapcha Glaciers are the parent glaciers of Imja Glacier and

Imja Glacial Lake. Till 1950, there was no lake at that location but a couple of ponds as seen on the topographical map known as the 'Schneider Map', Khumbu Himal (1:50,000), which was based on terrestrial photo-grammetry and field work carried out during 1956 to 1963.

Glaciers feeding the Imja lake are debris covered glaciers and the lake is dammed by the ice-cored end moraine. The termini of lake-calving glaciers are melting very fast—faster than ice flow can advance the front—and as a result the Imja Lake is getting bigger year by year as the glacier shrinks.

On the left bank across the lateral moraine another clear water Ampulapcha glacier lake is developing and is also getting slowly bigger with time. Considering the color of the water of Ampulapcha Lake and also the similar colors of smaller isolated ponds on the end moraine, it is possible that these lakes are completely separated from the Imja Lake and there is no direct contact of water with two of those lakes (See Below Pictures). This is also supported by the differing water levels if Imja Lake and Amphulapcha Lake. Only the turbid Imja Lake together with its continuous set of ponds and connecting streams across the end moraine are hydraulically connected, and it is these upon which we have focused our investigation.

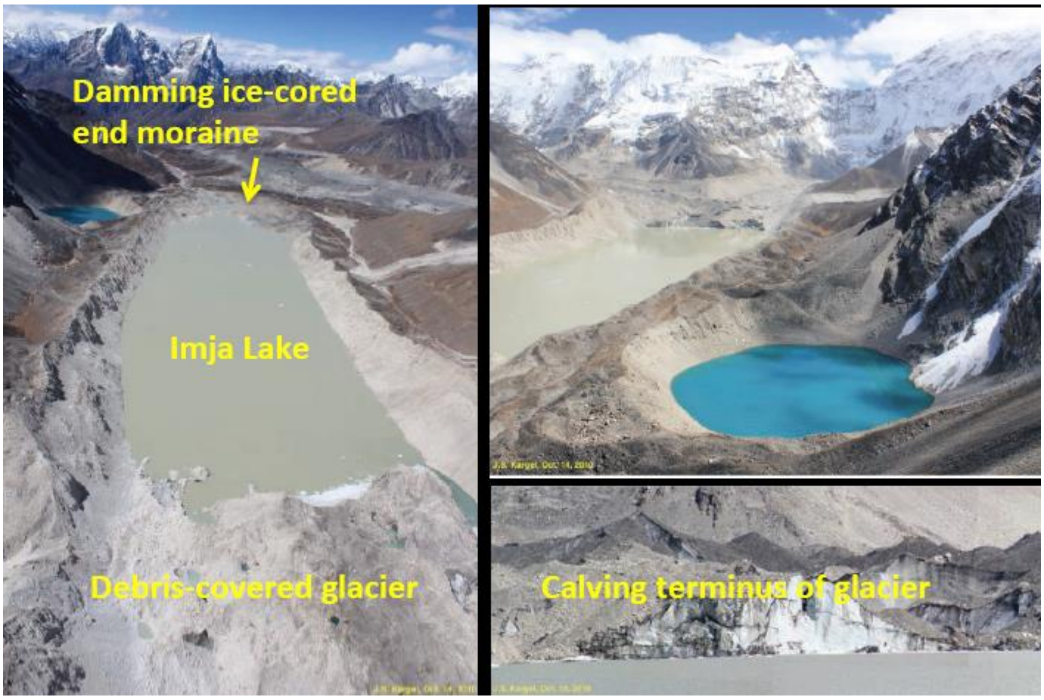


Figure 1.2 Picture shows the Imja and blue-water Amphulapcha Lake together with the calving terminus of the imja glacier. Photos by Kargel, taken from a helicopter Oct 2010.

The lake is separated in three parts one big lake and two small lakes along the out let channel. The Lake was just 0.03 km^2 in 1962 but increased to 1.06 km^2 in 2009 and now is identified as among the fastest growing lakes in the entire Himalayan region. Realizing the potential threat due to Imja Lake, it has been the target of various studies. From 1991, several study teams have conducted topographic and bathymetric investigations to find out the lake area, depth, volume

of water stored and stability of the end and lateral moraines. However, the studies conducted so far were not sufficient to gain an adequate understanding of the risk associated with Imja Lake, although with each successive study and each year of growth of Imja Lake there has been an increased scientific recognition that this lake poses a serious danger of a glacier lake outburst flood. Thus, this study has been carried out to better assess the risk and to lower the lake water level to safer level.

1.3. Glacial lake outburst floods

Meltwater lakes are potentially unstable; the sudden catastrophic release of water from such a lake is known as a glacial lake outburst flood (GLOF). In Nepal, until the sudden outburst of Dig Tsho Lake on 4th August, 1984 occurred, very little attention was given to this phenomena.

Figure 1.3 Complete aerial view of source of Imja Glacier Lake and the natural outlet. Photo from ICIMOD, 2009.

The event caused death of three persons and destroyed one hydropower plant (worth US$ 1.5 million), 14 bridges and 35 houses. The outbreak of Dig Tsho caused more than three million dollars' worth of damage and disrupted the downstream community of Khumbu for several months. The alarm bells sounded by this outburst event put in motion a plethora of scientific investigations, including, surveys, research, and preliminary estimates of downstream vulnerability among others (ICIMOD 2011). The Water and Energy Commission Secretariat (WECS) of then-His Majesty's Government, the International Centre for Integrated Mountain

Development (ICIMOD), and the United Nations University (UNU) collaborated in the work that eventually produced the first detailed assessment of a GLOF event in Nepal (WECS internal report 1987; Ives 1986; Vuichard and Zimmermann 1986, 1987).

A number of GLOFs have been reported in the region in the last few decades, particularly from the eastern region (Mool and others, 2001; Yamada, 1998; Richardson & Reynolds, 2000). Altogether Nepal has experienced at least 24 GLOF events in the past. Of these, 14 are believed to have occurred in Nepal itself, and 10 were the result of flood surge overspills across the China-Nepal border. Risk of damage and loss of life continues as the flood surges downstream across the river valleys displacing human settlements and investments. Regarding the glacial lake outburst floods that occurred in Nepal, there were altogether 14 GLOF events that had occurred in Nepal. The detailed information of these GLOF events is shown in Table 1.

Table 1.1 GLOF events recorded in Nepal and Tibet (highlighted GLOF's are originated in China and effected Nepal)

No.	Date	River basin	Lake	Cause
1	450 years ago	SetiKhola	Machhapuchchhre	Moraine collapse
2	1935	Poiqu (Bhote-Sun Koshi) basin	Taraco lake	unknown
3	1964	Trishuli River Basin	Longda Glacier lake	unknown
4	1964	Poiqu (SunKoshi) Basin	Zhangzangbo	unknown
5	1964	Pum Qu (Arun) Basin	Gelhaipu Co	unknown
6	1968, 1969, 1970	Pum Qu (Arun) Basin	Ayico	unknown
7	3-Sep-77	Dudh Koshi	Nare	Moraine collapse
8	23-Jun-80	Tamor	NagmaPokhari	Moraine collapse
9	1981	Poiqu (Sun Koshi) Basin	Zhangzangbo 2nd time	unknown
10	1982	Pum Qu (Arun)	Jinco	unknown
11	4-Aug-85	Dudh Koshi	Dig Tsho	Ice avalanche
12	12-Jul-91	Tama Koshi	Chubung	Moraine collapse
13	3-Sep-98	Dudh Koshi	Tam Pokhari	Ice avalanche
14	15-Aug-03	Madi River	Kabache Lake	Moraine collapse
15	8-Aug-04	Madi River	Kabache Lake	Moraine collapse
16	Unknown	Arun	BarunKhola	Moraine collapse
17	Unknown	Arun	BarunKhola	Moraine collapse
18	Unknown	Dudh Koshi	Chokarma Cho	Moraine collapse

19	Unknown	Kali Gandaki	Unnamed (Mustang)	Moraine collapse
20	Unknown	Kali Gandaki	Unnamed (Mustang)	Moraine collapse
21	Unknown	Mugu Karnali	Unnamed (Mugu Karnali)	Moraine collapse

Sources: *Bajracharya et al., 2008; Damen, 1992; Dwivedi, 2000 & 2005; Dwivedi et al.al, 1999; Galay, 1985; Ives et al., 2010 ; Lanzhou Institute of Glaciology and Geocryology (LIGG), Water and Energy Commission Secretariat (WECS), Nepal Electricity Authority (NEA), 1988; Mool et al., 1995, 2001; Yamada, 1998.*

Evaluation of the possibility of catastrophic drainage is based on the characteristics of a lake, its dam, associated glaciers, and other topographic features (Mool et al. 2001a). The factors taken into account include the size; rate at which the lake is expanding; position with respect to the associated glacier; height of the moraine dam; overtopping height (free board); origin of the lake (supraglacial, cirque, moraine dammed); physical condition of the surroundings, such as the existence of hanging glaciers or potential rock and debris fall or slides; and the volume of water that could drain out. Based on these criteria, ICIMOD 2010 has identified 21 potentially critical glacial lakes and prioritized the risk level and priority of these lakes. The socioeconomic and physical parameters were considered together and the critical lakes were categorized into: 1) high priority "Category I" lakes– requiring extensive and most urgent field investigation and mapping; 2) medium priority "Category II" lakes – that require close monitoring and reconnaissance field surveys; and 3) lowest priority "Category III" lakes – that warrant periodic observation. Of the 21 lakes reviewed, 6 were classed as Category I, 4 as Category II, and 11 as Category III. It should be noted that Imja Lake is among the Category I lakes, as is Tsho Rolpa, which is Nepal's only highly engineered glacial lake.

Table 1.2 List of potentially critical glacial lakes in Nepal identified by ICIMOD in the 2010 study and their priority category

S. No.	Lake ID Number (2009)	Lake Name	Category
1	kotak_gl_0009	Tsho Rolpa	I
2	koaru_gl_0009	Lower Barun	I
3	kodud_gl_0184	Imja Tsho	I
4	kodud_gl_0036	Lumding	I
5	kodud_gl_0242	West Chamjang	I
6	gamar_gl_0018	Thulagi (Dona)	I
7	kotam_gl_0133	Nagma	II
8	kodud_gl_0241	Hungu	II
9	kodud_gl_0193	Tam Pokhari	II
10	kodud_gl_0229	Hungu	II
11	kotam_gl_0191	–	III
12	gakal_gl_0004	–	III

13	koaru_gl_0012	Barun	III
14	kodud_gl_0238	–	III
15	gabud_gl_0009	–	III
16	kodud_gl_0220	–	III
17	koaru_gl_0016	–	III
18	gakal_gl_0008	–	III
19	kotam_gl_0111	–	III
20	kodud_gl_0239	East Hungu 2	III
21	gakal_gl_0022	Kaligandaki	III

1.4. GLOF mitigation in Peru, Bhutan and in Nepal

1.4.1. Case of Peru

An updated glacier and glacial lake inventory indicates that there are 830 glacial lakes in the Cordillera Blanca, with 514 draining into the Río Santa watershed and then tothe Pacific Ocean. All 514 have areas greater than 5,000 m^2 and volumes between 100,000 m^3 and 79 million m^3**.** Many of these glacial lakes have caused natural disasters in the past while others currently pose significant threats. On the snow-covered slopes moraine dam failures have been frequent. Over the last three decades, increased climate variability has modified glacier stability and created conditions different from those studied prior to the 1970s. Prevention measures need to include new criteria and disaster risk analyses. Whereas climate change is affecting glacier stability, major engineering works on many of the lakes has altered—mainly reduced—the hazards.

Primary natural disasters in Peru

Peru has a long and fairly well documented history of glacier-related natural disasters (outburst floods and associated rock and ice avalanches and debris flows) going back to the 18th century (Table 1.3). However, it is possible that significant glacial retreats during the medieval warming period (800 to 1200 A.D.) also produced avalanches whose traces are visible on many slopes around the Cordillera Blanca, in areas such as Caraz, Marcará, and Callejón de Huaylas.

Safety measures adopted for glacial lakes in the Cordillera Blanca, Peru

The safety measures adopted for glacial lakes in the Cordillera Blanca have two primary objectives;

a) Decrease the volume of the lake, build structures to maintain the volume at desirable levels, and contain potential GLOFs resulting from falling ice.

b) Utilize the structures to regulate the lake as a reservoir, in light of potential future water shortages.

Table 1.3. Natural disasters in the Cordillera Blanca

Year	Event
1725	Outburst flood buries town of Ancash
1725	Avalanches and outburst floods in Huaraz
1883	Outburst flood in Macashca, close to Huaraz
1869	Outburst flood in Monterrey – Huaraz
1917	Outburst flood from Nevado Huascarán over Ranrahirca
1938	Outburst flood in the Ulta - Carhuaz ravine
1941	Outburst flood in Pativilca watershed
1941	Outburst flood in Huaraz (4,000 – 5,000 dead)
1945	Outburst flood over the Chavín de Huantar ruins
1950	Outburst flood in Jancarurish reservoir. Hydropower plant destroyed
1951	First outburst flood in Artesoncocha Lake – Parón Lake
1951	Second outburst flood in the Artesoncocha Lake – Parón Lake
1952	Outburst flood in Millhuacocha Lake – Quebrada Ishinca
1953, 1959	Outburst flood in Tullparaju Lake – Huaraz
1962	Outburst flood in Ranrahirca, in Nevado Huascarán (4,000 dead)
1965	Outburst flood in the Tumarina Lagoon – Carhuascancha
1989	Outburst flood in Huancayo, from an outburst of Chuspicocha Lake
1970	Magnitude 8 earthquake-triggered glacier ice and rock avalanche and outburst flood (sturzstrom) in Yungay and Ranrahirca (15,000 dead)
1998	Outburst flood in Machupicchu. Hydropower plant destroyed

Methodology for implementing safety measures in the Cordillera Blanca

The methodology that has been systematically followed in the Cordillera Blanca Glacial Lake includes following steps;

1. Carry out an initial assessment of the characteristics of the lake and surrounding glacier. In this phase, preliminary studies are carried out to include the study area in the inventory of glacial lakes. Carry out a more in-depth study. If the initial assessment finds characteristics that indicate there is a risk downstream, further study is warranted.
2. This includes cartographic and bathymetric studies of the glacial lake and surrounding terrain, glaciological studies of the glacier, geological studies, and analyses of the soil mechanics of the terrain. These studies should already begin to address the potential implementation of safety measures.
3. Analyze the hydrology of the watershed. This is equally important to determine safe discharge levels for the design of overflow canals, allowing for safe removal of excess lake volume.

4. Implement the safety measures based on information collected from the in-depth studies. Safety measures include volume reductions, hydraulic infrastructure such as open canals, and the drainage tunnel or channel that will be covered by the rebuilt dam to contain potential surges caused by falling ice.

1.4.2. Case of Bhutan

The glacier inventory in Bhutan was undertaken in 2001 (Mool et al., 2001). From the inventory a total of 677 individual glaciers were indentified with approximate area of 1,317 km^2. Similarly, a total of 2,674 glacial lakes have also been indentified, of which 25 are classified as potentially dangerous (Fig. 8).

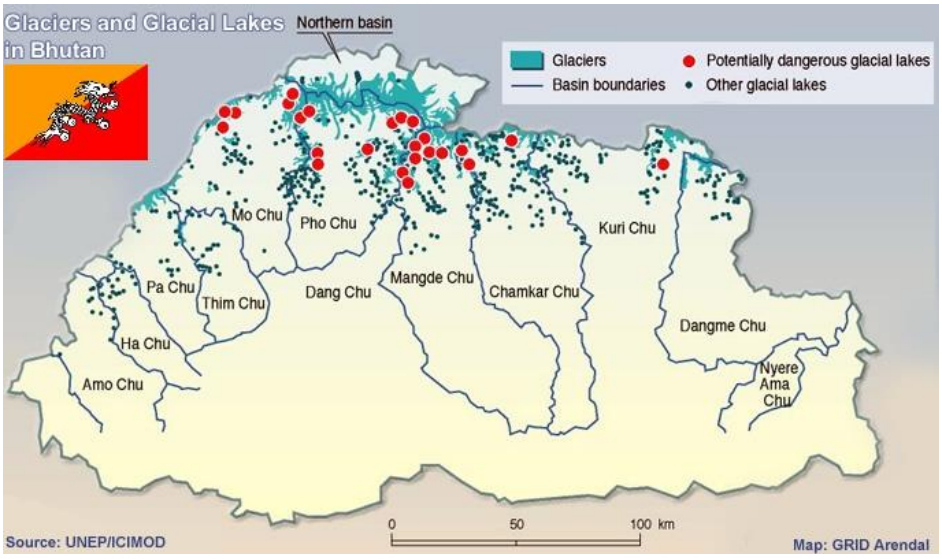


Figure 1.4. Map of Bhutan with glacier and glacial lakes

After 7 October 1994, when a GLOF occurred from Luggye Lake the Royal Government of Bhutan started conducting different monitoring and awareness campaigns in order to mitigate the adverse impact of GLOF. In 1998, the Japan-Bhutan joint research project updated the inventory of major glacial lakes and prepared an assessment of GLOF including ranking of potentially dangerous lakes. A study of 66 glaciers in Bhutan Himalaya revealed an average retreat of 8.1 % from 1963 to 1993 (Karma et al., 2003). In 1963, the area covered by glaciers was 146.9 km^2; by 1993, this had been reduced to 134.9 km^2. Later Karma et al. (2008) concluded that the growing Thorthormi Glacial Lake had a potential for outburst in the near future. At present, there are 25 lakes in Bhutan identified as potentially dangerous and warranting further investigation.

1.4.3. Case of Nepal

Tsho Rolpa glacier lake which is located in the Rolwaling Valley, Dolakha district in the central Nepal Himalayas was considered potentially most dangerous glacial lake in Nepal especially

before carrying out engineering works in 2000 to lower the lake water level to reduce the level of risk from a potential GLOF.

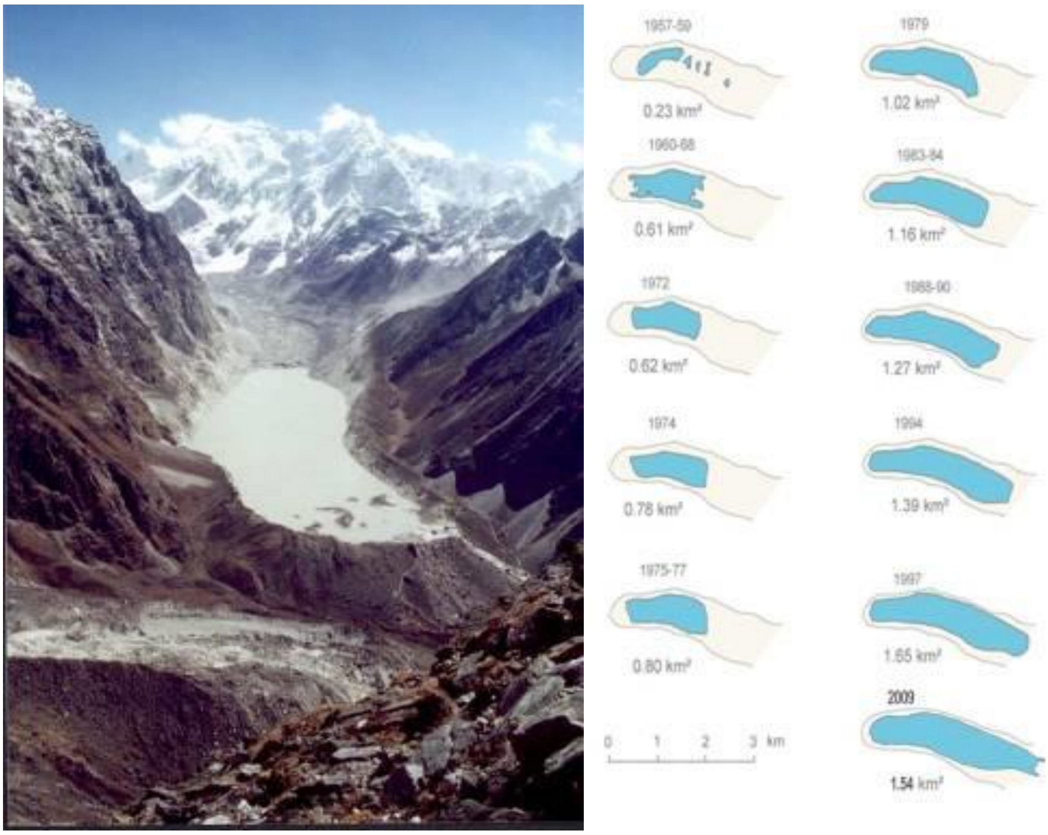


Figure 1.5. shows Tsho Rolpa Glacial Lake and its development stages in different years

The lake had been rapidly expanding on the terminal part of the debris-covered Trakarding Glacier at least since 1958 (surface area 0.23 km^2) when the Survey of India performed a topographic survey to late 1990s (surface area 1.55 km^2 in 1999) before carrying out mitigation works (Chikita et al., 1999; ICIMOD, 2011).

According to ICIMOD (2011), maximum and average depth of the lake was 133.5 m and 56.4 m, respectively with surface area 1.54 km^2 and estimated volume of water stored 85.96 x 10^6 m^3, whereas the lake was 3.45 km long as of 2009. Owing to an accelerated growth of the lake, rapid degradation of damming moraines (terminal and lateral), melting of dead-ice inside the moraine, presence of seepage of the lake from the end moraine, and rapid ice calving from the active glacier-terminus were attributed for the high GLOF hazard at the lake (Rana et al., 2000). As a result of perceived high GLOF hazard at the lake, mitigation measures including the lake water level lowering and early warning system were recommended and implemented. Despite of some reduced hazard level of a potential GLOF at the lake following the mitigation works, Tsho Rolpa is even now regarded as one of the most critical glacial lakes in Nepal and the lake is being continuously monitored by the DHM.

Chapter Two

2 PRIOR STUDIES OF IMJA LAKE

2.1 Prior studies of Imja Glacier/Lake dynamics, updated here to 2014

Imja Glacial Lake is located in the easternmost part of the Sagarmatha region in Solukhumbu district, Nepal. Lhotse Shar, Imja and Ampulapcha Glaciers are the parent glaciers of Imja Glacier and Imja Glacial Lake. The Imja Glacial Lake at the toe of the Imja Glacier is located at latitude 27° 59' N and longitude 86° 56' E in the Nepalese Himalayas.

2.1.1. Satellite time series

No lake can be seen on the photographs taken in 1956 by Muller (Swiss Everest/Lhotse Expedition of 1956), in 1963 by Bishop and probably in 1971 by Yamada (1998). No lake but a couple of ponds can be found on the topographical map known as the 'Schneider Map', Khumbu Himal (1:50,000), which was based on terrestrial photo-grammetry and field work done from

1956 to 1963. The map shows only a couple of small ponds on the glacier tongue with a total area of 0.03 km^2 as shown in the map of Imja Glacial Lake development.

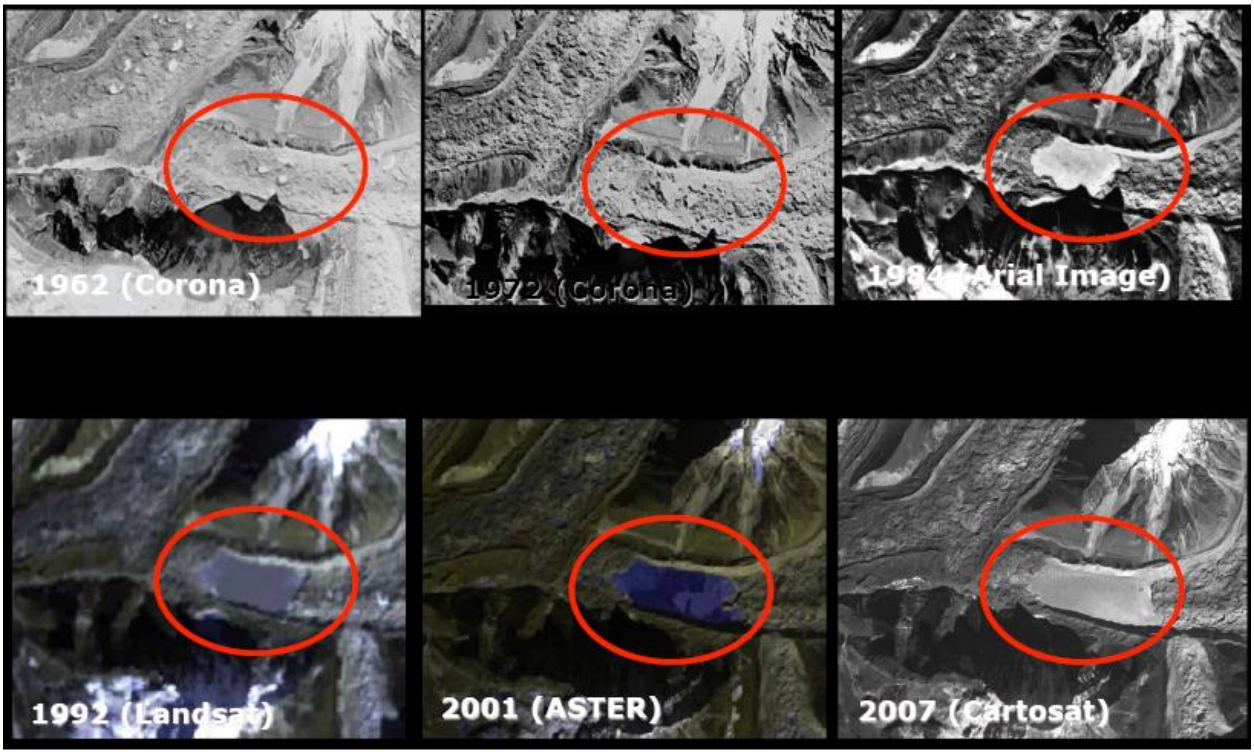


Figure 2.1: Shows the formation and growth of Imja Lake, 1962-2007 (Realized by Tobias Bolch (1984-image courtesy of D. Benn) Bolch et al. 2008, NHESS.

The lake was first recognized in the terrestrial oblique photographs taken in 1975 by a Japanese glaciological research team (Japanese Glaciological Expedition of Nepal, GEN). The aerial oblique photographs taken in 1975 and 1978 by GEN show a large lake with islands and peninsulas. The size of the lake was estimated to be around 0.40 sq. km in 1984. The islands and peninsulas disappeared, probably by melting. According to the result of the field survey made in early April 1992 area of the lake expanded to 0.60 km^2 (Yamada, 1992). The age of the lake as of 2010 may be estimated to be about 55 years. Imja Glacial lake with an area of 1.06 km^2 as of May 2009 (ICIMOD, 2011), was recorded as one of the fastest-growing lakes in the entire Himalaya.

Figure 2.2: Shows declassified 1962 Corona image of the Lhotse/Imja area. There was no Imja lake then.

2.1.2. Prior land surveys

The first topographic survey of Imja Glacial Lake was done in April 1992 by Yamada (1992). At that time the length and width of the lake were 1.3 km and 0.5 km, respectively. The lake occupied an area of 0.6 km^2 and the accumulation of water was estimated at about 28 million m^3.

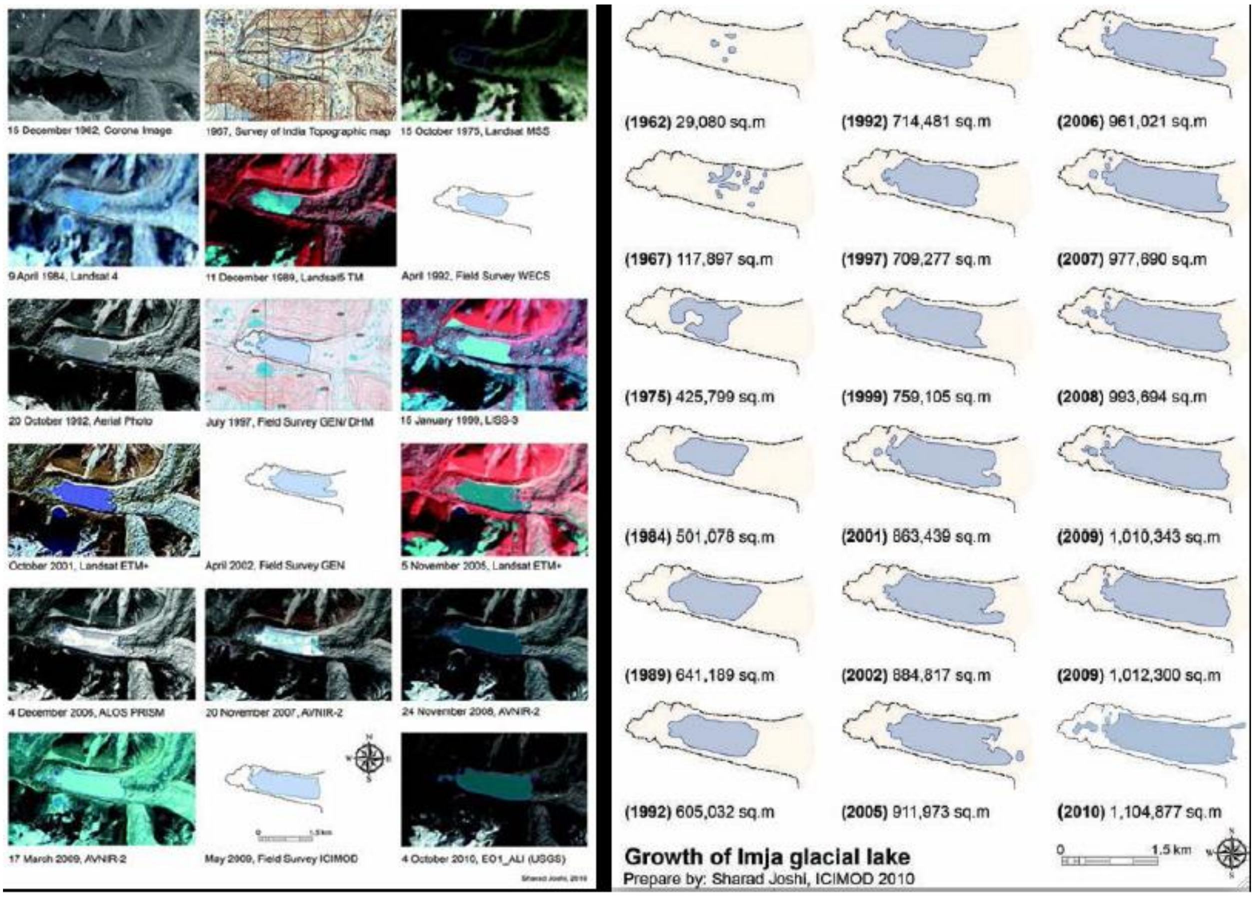


Figure 2.3. Imja Lake development series gatherd by Sharad Joshi (ICIMOD 2010)

A topographical survey was carried out at the end moraine and the dead ice area of the Imja Lake in October 2001 and in April 2002 by the team of Akiko Sakai (Sakai et al., 2007). The survey was carried out by using a digital theodolite with a laser distance meter and differential Global Positioning System (d-GPS). The topographic map of dead ice and end moraine is given in figure below. They observed a significant change in spillway on the dead ice area as compared with the research done by Watanabe et al. (1995). They observed the spillway along the southern side the cone as opposed to its northern side in 1994. They also concluded no possibility of GLOF by collapse at the right moraine, however if the end moraine or dead ice to melt or collapse, a GLOF would occur. Similarly, if the left side of the moraine and dead ice area were to completely collapse, the lake water up to 30 m depth would flow away.

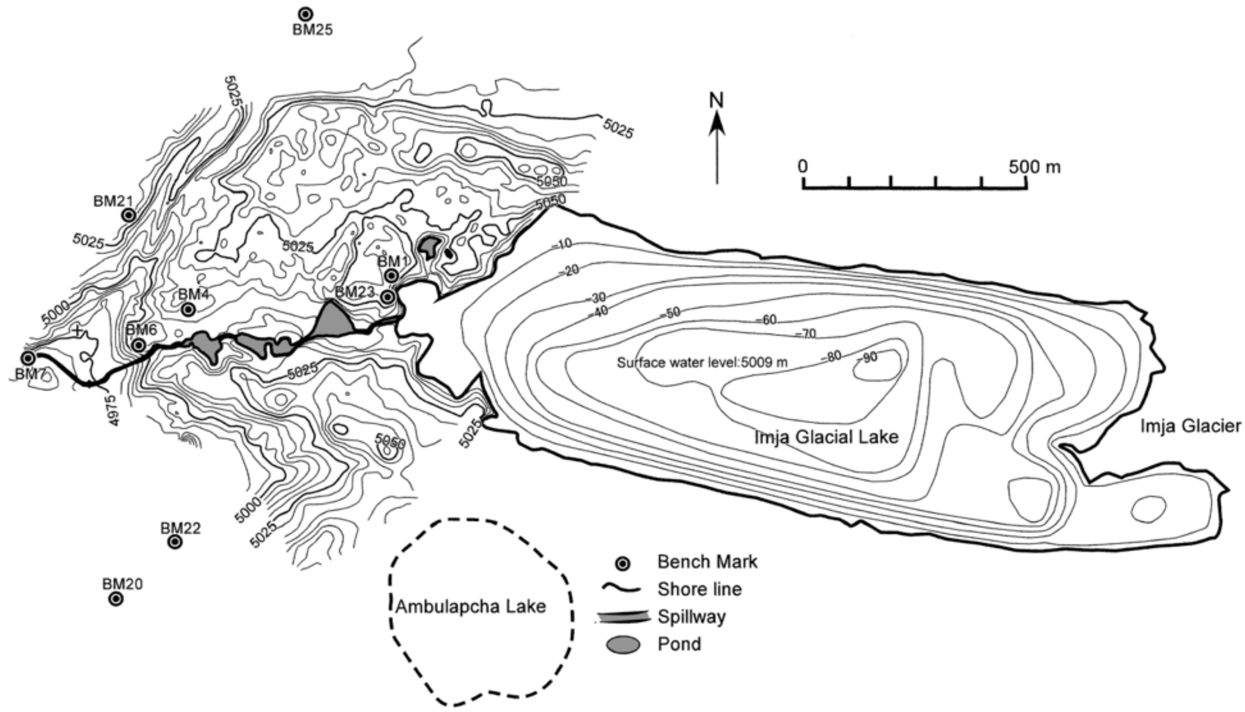


Figure 2.4:. Topographic map of end moraine of Imja Glacier and bathymetric map of Imja Glacier. The end moraine has thermokarst-type features indicative of dead ice. Contour intervals of the end moraine/dead ice area was at 5-m intervals. Depth contour interval of the lake is 10 m; depths expressed as relative height to water surface level (5009 m a.s.l.) (Sakai et al., 2007).

The topographic survey of Imja Lake was undertaken from 4 May to 2 June 2009 by a team from ICIMOD with the help of various Nepalese academic and governmental organizations. The bench marks established during that time are used for the detail topographical survey during this study as well Figure below). The topography survey includes survey of end moraines along with the overflow channels, lateral moraines, the lake shorelines, and the glacier terminus. The topographic survey of 2009 concluded a further increase of 0.012 km^2 of lake area.

In support of UNDP/Nepal's Community Based GLOF and Flood Risk Reduction Project, ADAPT Asia-Pacific under the Prime Contract and Task Order AID 486-C-11-00005, has acquired the services of Kathmandu University (KU) to conduct a topographic survey and engineering design of the outlet channel at the end-moraine of Imja Glacial Lake

Figure 2.5. shows a some of thebenchmarks that was established in a prior survey under-taken by ICIMOD in 2009. Some of these were re-surveyed in the 2014 land survey team's work.

and pre-feasibility study of a mini-hydropower generation facility from drained water near Dingboche. The main objective of the project was to present detailed topographical survey and other relevant field data needed to design the outlet channel for controlled release of the Imja Lake water to reduce any GLOF risk.

Field investigation of the study area was done during 15 May to 4 June 2012 to carry out the topographic survey at the end-moraine and outlet portion of Imja Lake. The study team observed numerous hummocks of moraine complex along the lateral and end-moraine. Small traces of biological growth were also seen on the exterior face of the end moraine. The topographical survey comprises of traversing and contouring surveying. The traverse loop was referenced to control point (BM4) established by ICIMOD while bearing was derived from the local north using precise compass. The traverse loop consisted of seven control points including BM4. Similarly, detailed contour survey of Imja outlet was carried out based on the control points established through the traverse survey. The topographic data recorded included features, such as existing outlet river channel, and the lake boundary along with other depicting spot height necessary for site layout planning purposes. The survey work was carried out using both total station and GPS instruments (Fig. 2.3).

2.1.3. Field-based photographic time series

Because of the constraint of the resolution of the satellite images, the repeated photography is very valuable information to point out the exact changes within sort period of time in any area. Dr Byers is a well know name in repeated photography. Alton Byers has taken several photos of Imja Glacier and Imja Lake in recent years to repeat as photo half a century earlier, taken by Edwin Schneider, which shows no lake

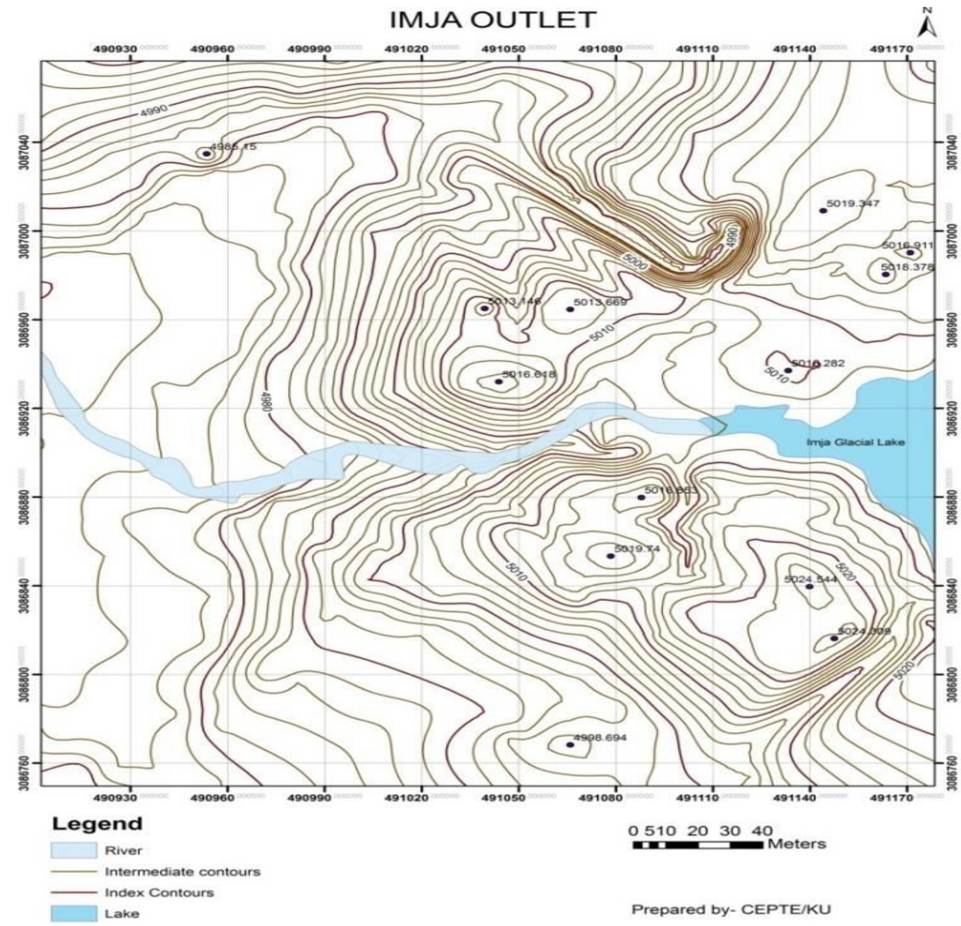


Figure 2.6: shows Topographic map of Imja Lake outlet

(Figure 2.6; see also Appendix 1 for more photos and the color originals by Alton Byers). The photos document a rapid evolution of the system, including rapid retreat and thinning of the glacier and elongation of the lake, which is also documented by satellite.

2.1.4. Overview of Imja Lake's state and dynamics

According to Watanabe etal., 1994, 1995, Imja Tsho is dammed by the 700 m wide by 600 m long ice-cored, debris-covered, former glacier tongue. The natural incision of the outlet channel complex (stream erosion and general ice core melting) has lowered the lake level by 37 m over the past 4 decades (Lamsal et al., 2011). The outlet lake complex is evolving into a new arm of the lake (Benn et al., 2012). Although the lake surface is slowly lowering, its area is increasing and we also show from our survey results (Chapter 4) the the depth is increasing, so lake volume is increasing at a rate of 2.51 million m³ per year (M A. Somos Valenzuela et al., 2014) or perhaps more rapidly, according to our new results).

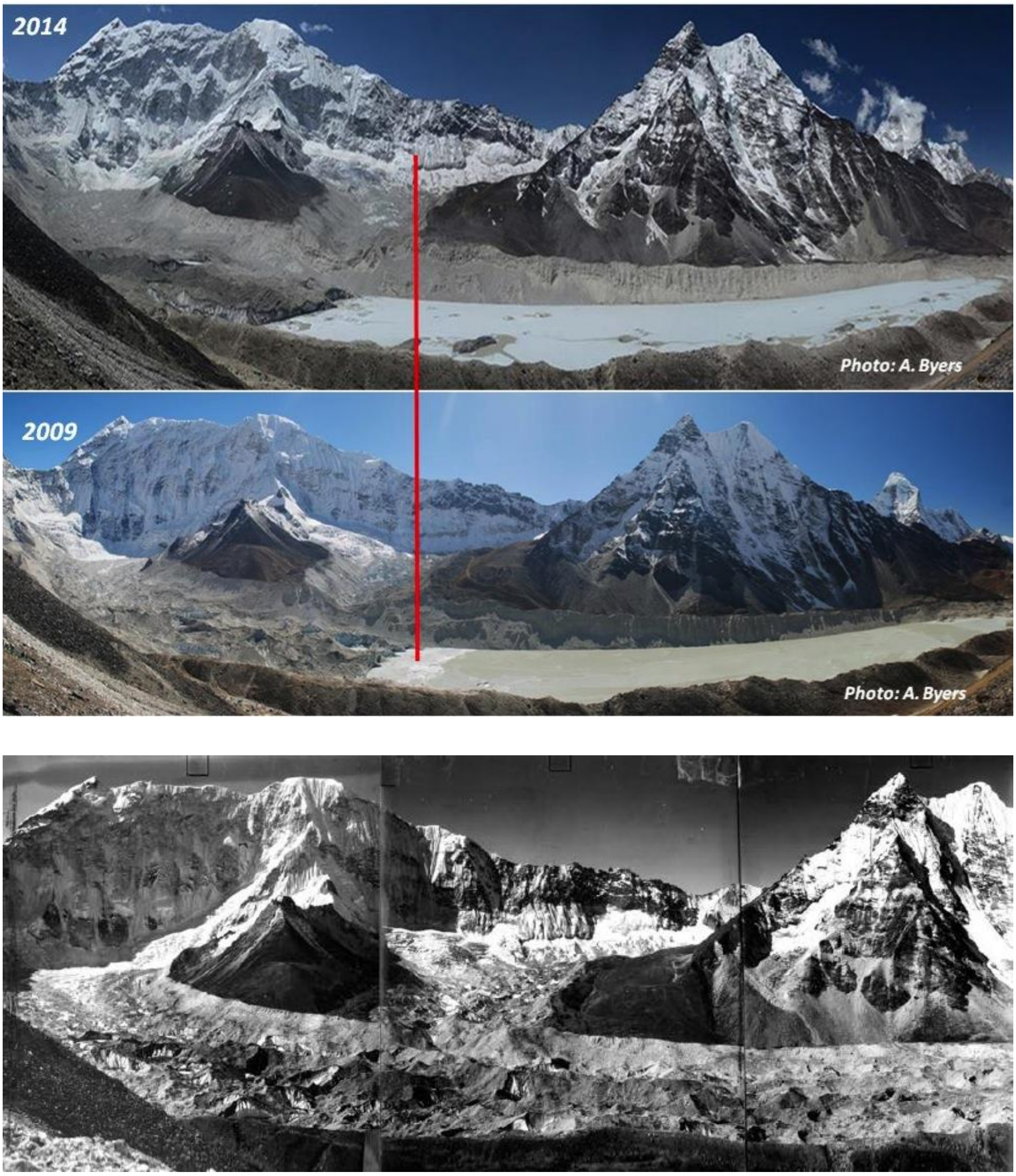


Figure 2.7: Two photos of Imja Lake and the calving margin of Imja/Lhotse Shar Glacier, taken in 2014 and 2009 by Alton Byers, and Erwin Schneider's 1956 photo of Imja Glacier from above Island Peak base-camp (Received from Dr Alton Byers). Imja Lake did not exist in 1956.

2.1.5. Prior studies on Imja Lake bathymetry, storage volume

The first Bathymetry survey of Imja Glacial Lake was done in April 1992 by Yamada (1992). At that time the average depth of the lake was 47 m and the maximum measured depth was 99 m. The lake occupied an area of 0.6 km^2 and the accumulation of water was estimated at about 28 million m^3.

Table 2.1: shows the area depth and the volume measurement done in different time from different groups of scientists.

Year	Area (km^2)	Average Depth (m)	Volume (10^6 m^3)	Maximum Measured Depth (m)
1992[1]	0.60	47.0	28.0	98.5
2002[2]	0.86	41.6	35.8	90.5
2009[3]	1.01	35.1	35.5	96.5
2012[4]	1.257 ±0.104	48.0 ±2.9	61.7 ±3.7	116.3 ±5.2
2014[5]	1.28 ±0.026 excluding ponds	58.8±3 excluding ponds	75.22 ±4.1 excluding ponds	149.8

[1] Yamada, T. and C. K. Sharma (1993), Glacier Lakes and Outburst Floods in the Nepal Himalaya, IAHS 218

[2] Sakai, K. Fujita, T. Yamada (2003) Volume Change of Imja Glacial Lake in the Nepal Himalayas, ISDB 2003

[3] ICIMOD (2011) Glacial Lakes and Glacial Lake Outburst Floods in Nepal. Kathmandu

[4]September 2012 survey reported by Somos-Valenzuela, M., D.C. McKinney, R.D. Rounce, and A. C. Byers (2012) Changes in Imja Tsho in the Mt Everest region of Nepal, The Cryosphere 8, 1661-1671. However, the volume uncertainty relies on an assumption that the extrapolations of data in unsurveyed areas are fairly accurate.

[5] This survey, October 2014. Area uncertainty calculated as one 10-m pixel width uncertainty in lake width. Average depth uncertainty estimated as the standard deviation of the mean of about 30 transverse and longitudinal profiles divided by the square root of the number of profiles (a modified standard error of the means, not relaying on the number of measured points but rather than number of profile lines). Percentage volume uncertainty (then translated to absolute volume uncertainty) is calculated as the square root of the sum of the squares of the two constituent uncertainties in area and average depth. The upper pond contributes an additional ~150,000 m^3, and the lower pond somewhat less, and Amphulapcha Lake has a measured volume of about 3.2 million m^3. Further details in Chapter 5.

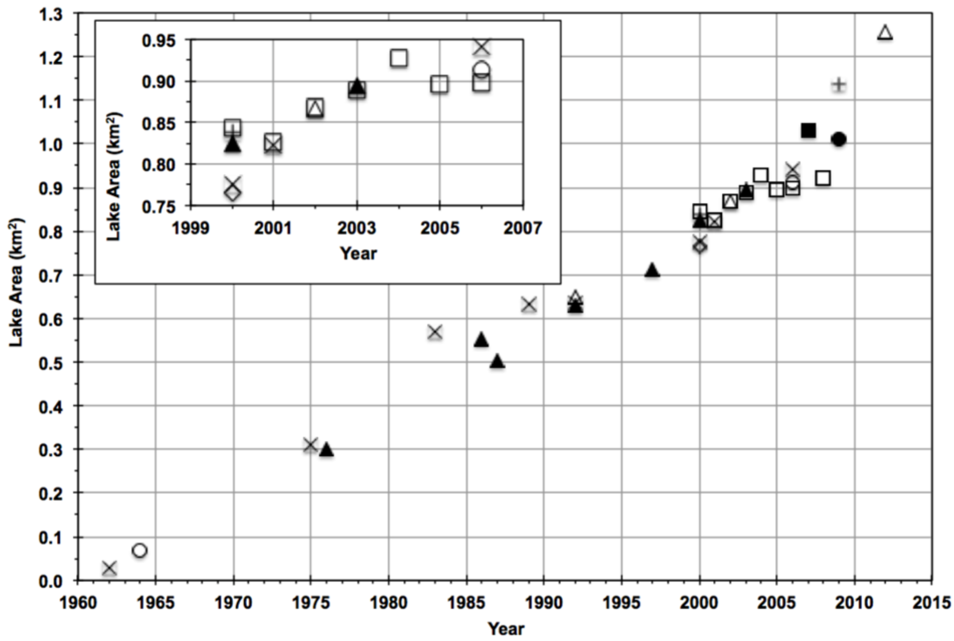


Figure 2.8: Area of imja Lake from 1962 until 2012. From Somos-Valenzuela et al. 2014.

It should be noted that all bathymetric surveys are subject to incompletion due to sampling density, so changes from one survey to another can reflect both actual changes and effects due to different or hopefully more complete sampling.

The bathymetric survey of Imja Lake was conducted by WECS in 1991 (WECS, 1991). During the survey the study team observed 99 m of maximum depth of Imja Lake. Further they calculated the melting rate at the bottom of the lake which was estimated to be 3.3 m year^{-1}. Later, in 1992 Yamada and his team performed bathymetric investigation on Imja Lake (Yamada and Sharma 1993). Later on April of 1992 and 2002 group of Koji Fujita conducted a bathymetric survey and compared the results with the survey done in 1992 by Yamada (Yamada 1998) (see figure below). In 1992, the depth measurements were made by a tape measure lowered through boreholes made with a fisherman's drill at 61 points (Yamada and Sharma, 1993). Measurements points only along a longitudinal line were surveyed by a dGPS in 2002. Shoreline of the lake was measured during both observations by a compass and a laser-distance meter from each depth measurement point near the shoreline was also used. The comparison of two bathymetric surveys revealed no significant lowering of lake bottom due to the insulation effect of thick debris on the ice beneath the lake and a continuous supply of debris. However, a drastic expansion of the lake was observed due to retreat of the upstream glacier.

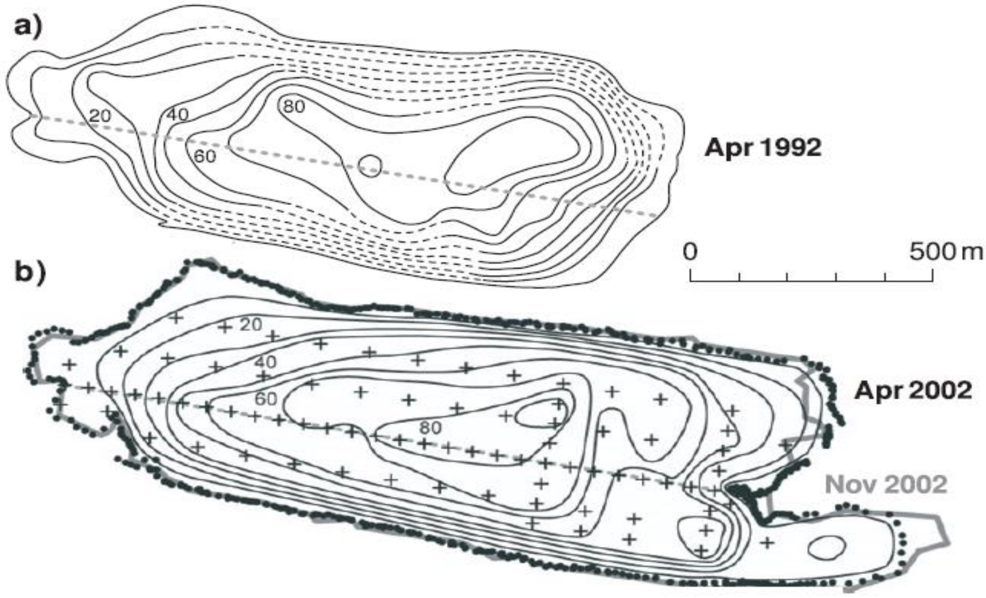


Figure 2.9: Bathymetries of Imja Glacial Lake measured in (a) March 1992 (Yamada, 1998) and (b) April 2002.

The bathymetric survey by a team of ICIMOD was carried out from 4 May 2009 to 2 June 2009 with a help of 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. Bathymetric maps were then prepared and the surface area and storage volume of the lakes were calculated (Fig. 2.6).

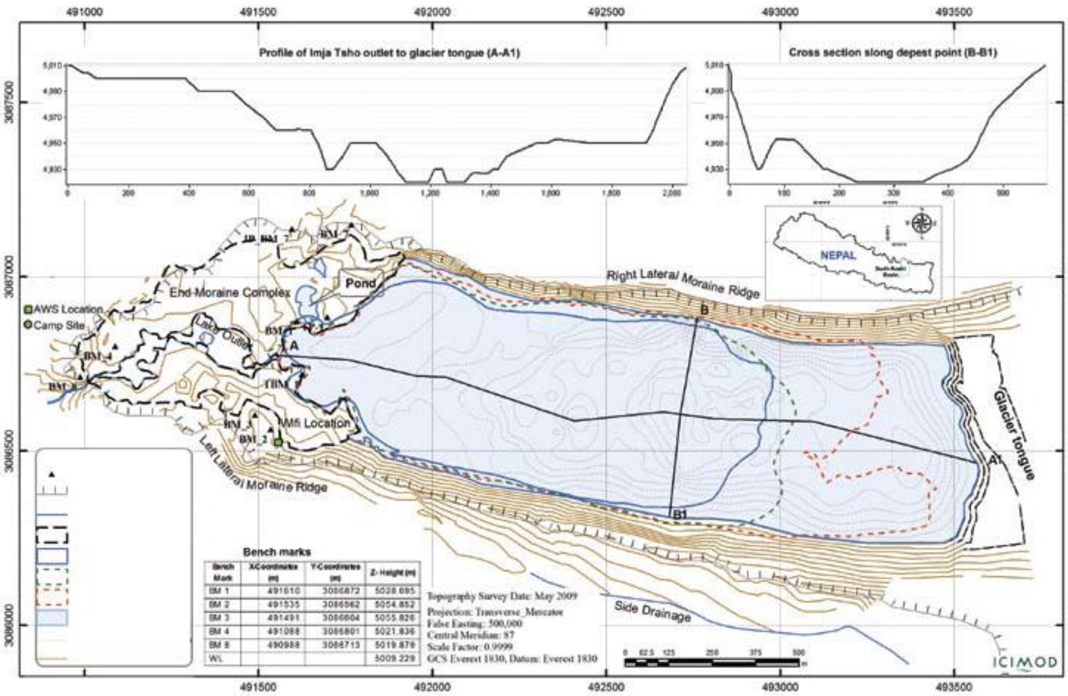


Figure 2.10. Bathymetric and topographic map of Imja Lake showing the longitudinal profile and cross-section along the deepest point (ICIMOD, 2011)

A bathymetric survey conducted by a team of Somos-Valenzuela between September 22 and 24, 2012 using a Biosonic EchoSounder MX sonar unit mounted on an inflatable raft (Somos-Valenzuela et al., 2013). Several transects were measured across the lake, as well as the lake outlet complex of the former glacier tongue of the lake (Fig. 28).

According to the survey the maximum measured depth increased from 98 m to 116 m from 2002 to 2012, and the lake's estimated volume grew from 35 million m^3 to 66 million m^3. Most of the expansion of the lake in recent years has taken place in the glacier terminus/lake interface to the east (Figures 2.3, 2.9, 2.10), with very little expansion taking place to the west.

Figure 2.12 shows the 2012 results along with those of 1992 and 2002, indicating an eastward expansion of the lake, rapid retreat of the glacier ice cliff. We agree with Somos-Valenzuela et al. (2014) that the evidence suggests that subaqueous melting has taken place, explaining the rapid eastward deepening. Our new data has extended this generally picture, though the situation is complicated by the fact that Somos et al. (2014) were unable to get very near the terminus due to dense iceberg coverage; hence, they extrapolated their data as indicated in the modified Figure 2.10.

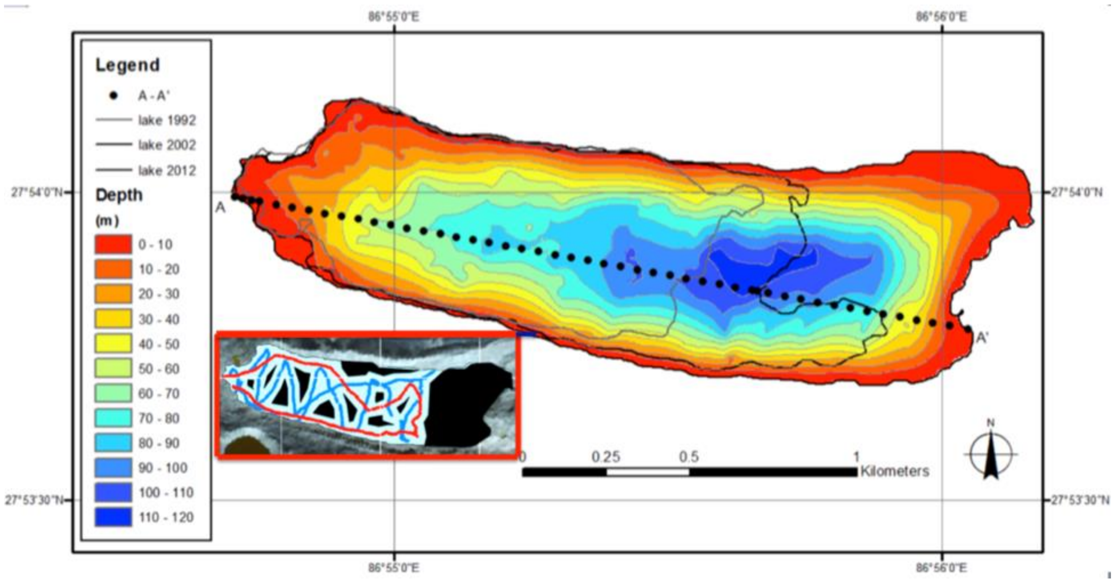


Figure 2.11. shows survey results from Imja Lake in September 2012 (Somos- Valenzuela et al., 2014). This was the most complete survey undertaken prior to our most recent survey. We have modified this original figure with addition of an inset, which shows the tracklines provided by Somos et al., and in black we show areas where the bathymetry was severely extrapolated or interpolated more than about 85 m from the nearest trackline. More than half the lake area is more distant than 50 m from a trackline. Furthermore, in the deepest portions measured by Somos et al., depth uncertainties were large (up to 5 m). Hence, there was a need to improve the bathymetry.

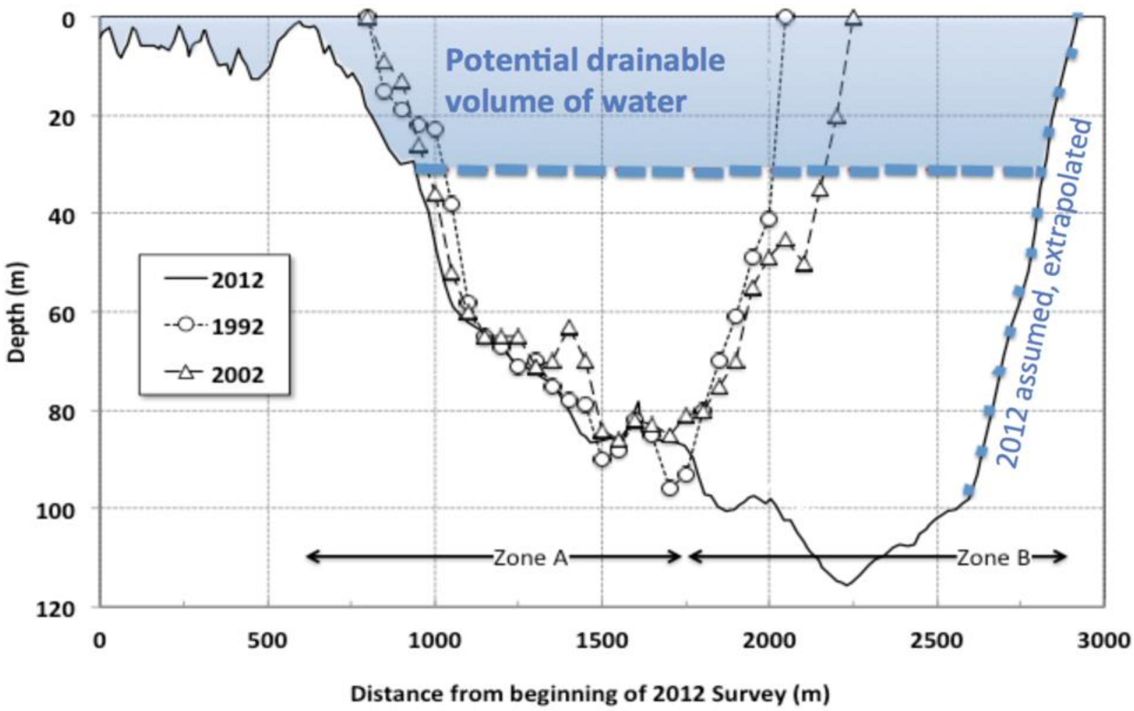


Figure 2.12: Approximate longitudinal profiles of the lake measured in different years. Figure modified from Somos et al. 2014.

One of the important factors in assessing the GLOF risk of Imja Lake is the immense volume that could be released in the event of a flood, and accurate bathymetric data are essential for estimating that volume. Somos et al (2012) estimated that the volume of a GLOF today could be 36 million m^3, an increase from the previous estimate of 21 million m^3 in 2002 (Sakai et al. 2003). Our new survey does not greatly increase this estimated drainable volume, as most of our estimated volume change over the volume estimated by Somos et al. occurs at depths below the drainable level, i.e., elevation in front of the damming end moraine.

Chapter Three

3 NEW SATELLITE BASED DYNAMICAL STUDIES OF IMJA GLACIER/LAKE

3.1. Recent geomorphological state of Imja Glacier and environment

Imja Glacier is located in the Imja Khola watershed in the Khumbu region of the Nepal Himalaya (27.9° N, 86.9° E), about 9 km south of Mt. Everest, a few kilometers south of Lhotse Peak, the highest and fourth highest peaks in the world, respectively. The area of the Imja basin is about 141 km², altitudes range from 4355 to 8501 m, and approximately 38 percent of the basin is covered by glaciers (Konz et al., 2005). Hammond (1988) identified twenty-four glacier lakes and numerous other meltwater ponds in the Khumbu region in 1988. Most of these lakes began forming in the late 1950s to early 1960s, and have expanded considerably since then, especially Imja Tsho (lake) (Figure 2). For example, the 1963 Schneider map of the Everest region does not show a lake on the Imja glacier, but rather five small meltwater ponds on the surface near the glacier's terminus (Hagen et al. 1963).

Figure 3.1. Names of glaciers and a few geomorphological features of the area near Imja Lake.

A number of authors have discussed the lake's historic development in detail (Quincey et al. 2007; Bajracharya et al. 2007; Byers 2007; Yamada 1998; Watanabe et al. 2009; Ives et al. 2010; Lamsal et al. 2011) . Bolch et al. (2011) studied the mass change for ten glaciers in the

Khumbu region south and west of Mt. Everest, and found that the Imja glacier area (including the Lhotse Shar glacier) exhibited a specific mass balance of -0.5±0.09 m/yr, the largest loss rate in the Khumbu region. This high annual mass loss rate appears to result from a complex combination of processes that include recently accelerating calving of the glacier terminus and comparatively thin debris cover that results in the daily transfer of heat directly from the heated debris to the ice below (Byers 2007).

Imja lake is bounded to the east by Imja glacier, to the north and south by lateral moraines, and to the west by the ice cored end moraine. The lateral moraine troughs act as gutters, trapping debris derived from rockfall, snow avalanches, and fluvial transport (Hambrey et al., 2008). Large, rapid mass movements, however, could easily overrun or even penetrate the lateral moraines and reach Imja Lake.

Imja lake is dammed by a 700 m wide by 600 m long, ice-cored, debris-covered, former glacier tongue through which water exits by means of an outlet lake complex (Watanabe et al. 1994; Watanabe et al. 1995; Somos-Valenzuela et al. 2012). The incision of the outlet channel complex has lowered the lake level by some 37 m over the last four decades (Hambrey et al., 2008; Watanabe et al., 2009; Lamsal et al, 2011). The bottom of Imja lake is most likely dead ice in places. The presumed melting of ice in the end moraine has caused the lake level to fall in recent decades (Watanabe et al. 1995; Fujita et al. 2009). Knowledge of the vertical lowering of the Imja glacier, lake, and former glacier tongue is minimal. Lamsal et al. (2011), however, report that the average lowering of the glacier surface for the period 1964 to 2006, in the area west of the lakeshore, was 16.9 m. The average glacier lowering east of the lakeshore during this period was 47.4 m. The former glacier tongue still contains ice as clearly evidenced by outcrops of bare ice, ponds formed by melt water from ice in the moraine, traces of old ponds, and results of a recent GPR survey (Somos-Valenzuela et al. 2012; Yamada and Sharma 1993). It is likely that the outlet lake complex is evolving into a new arm of the lake (Benn et al 2012). The outlet flow from the lake forms the Imja Khola (river), which is a tributary of the Dudh Kosi. As illustrated in Table 1, Imja lake has expanded over the last 50 years mostly through calving of the eastern end of the glacier (Hambrey et al., 2008). The western, down-valley expansion has stabilized in recent years while the eastern expansion continues unabated (Watanabe et al., 2009). For example, we observed extensive calving of the eastern glacier terminus, estimated at more than 200 m of ice loss, between May and September of 2012.

3.2. Recent regional surface changes assessed from an ASTER image pair

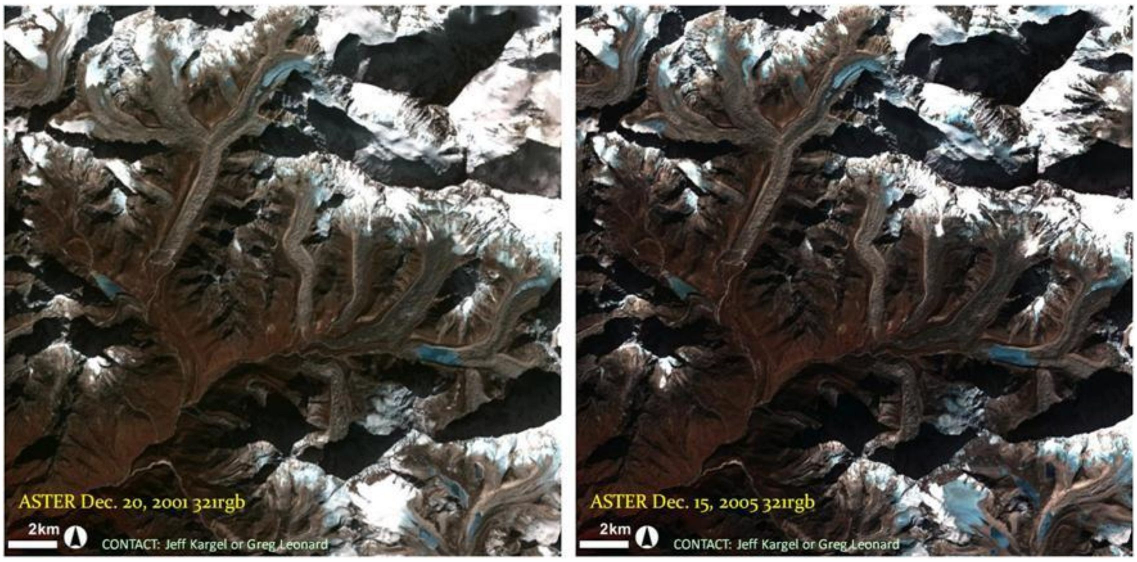


Figure 3.2. ASTER sequence shows 4 years of change in the Mt. Everest area: Khumbu Glacier, Imja Glacier and others. This sequence is best viewed in Apendix 1 together wit the difference image, which picks out changes that took place in the 4 intervening years.

ASTER two-scene image sequence shows 4 years of change in the Mt. Everest area, Khumbu Glacier, Imja Glacier and others. These are examples of stable glacier termini with stagnating debris-covered toes. In some cases in this area, glaciers are known to be down wasting (thinning) and slowly losing mass along their debris-covered tongues. Well-studied examples are Langtang and Khumbu Glacier.

3.3. Recent glacier flow speeds assessed from an ASTER image pair

Flow speeds assessed from ASTER images repeated 1 year apart shows that the Lhotse-Shar Glacier remains the most active among the three major branches of the Imja-Lhotse Shar-Amphu Laptcha Glacier system. It is flowing at a maximum of ~25 m/year in a heavily crevassed zone, but flow speeds drop off to about 1-5 meters per year near the calving terminus. The Imja Glacier has flow speeds only about 2-6 meters per year where we could measure.

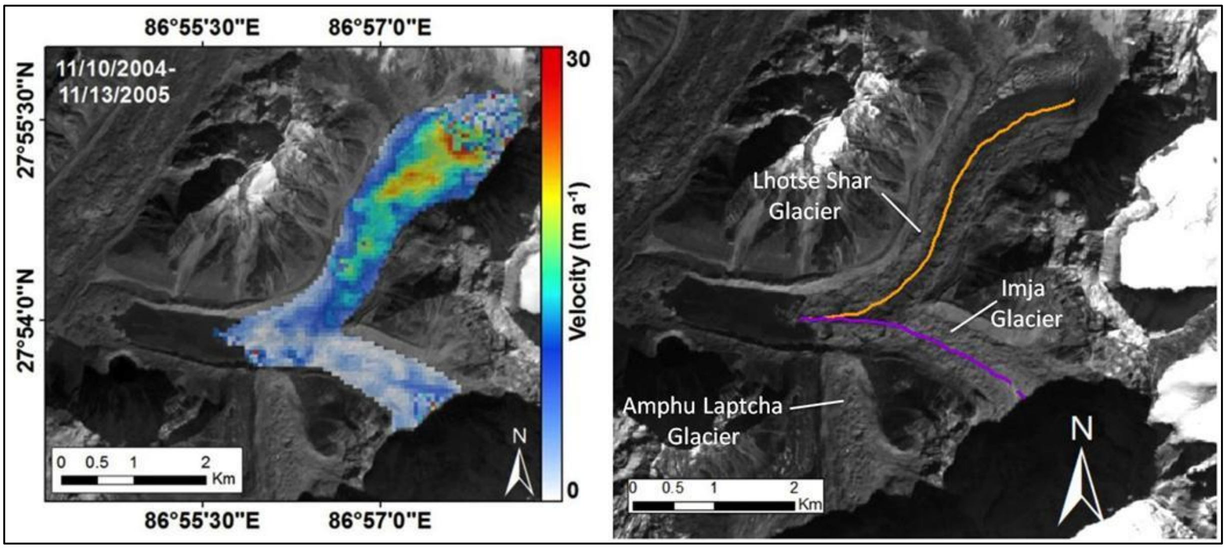


Figure 3.3: Flow speeds assessed from ASTER images repeated 1 year apart, and centerlines for flow speed profiling.

Amphu Laptcha Glacier has barely detectable flow, locally attaining around 5 m/year. As a consequence of its slight activity, it has detached from the former junction with Imja Glacier. Amphu Laptcha glacier is sagging in the center and has an elevated terminus. These conditions of sluggish flow and a sagging profile favor the development of glacier lakes in the near future. Imja Glacier might not be far behind, and even Lhotse Shar Glacier could see growth of supraglacial ponds. All three glaciers have pond formation, but it is not clear whether there is a growth trend of these ponds.

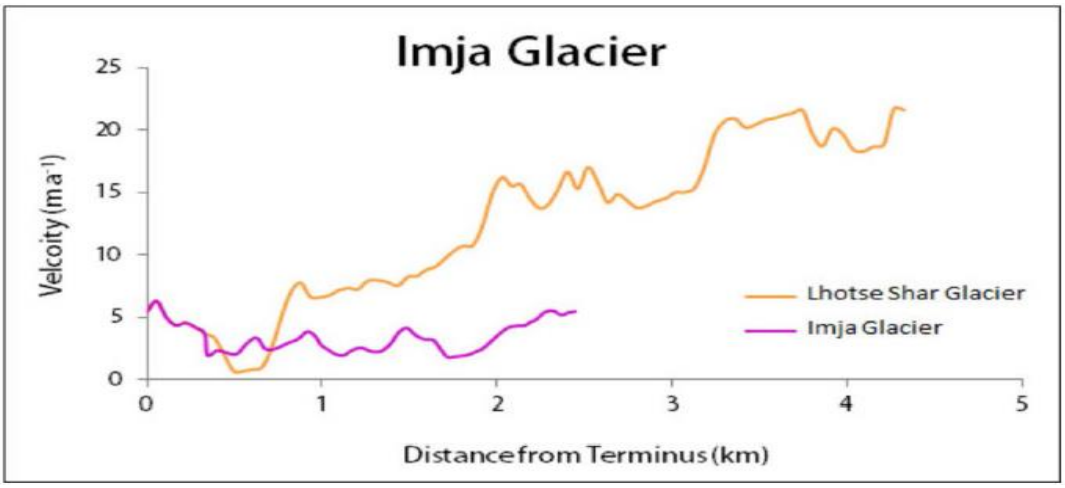


Figure 3.4: shows Longitudinal profiles of glacier flow speeds 10 Nov 2004 – 13 Nov 2004, calculated from correlation mapping of two ASTER images.

3.4. Multi-satellite time series showing glacier flow and calving margin retreat, and growth of Imja Lake

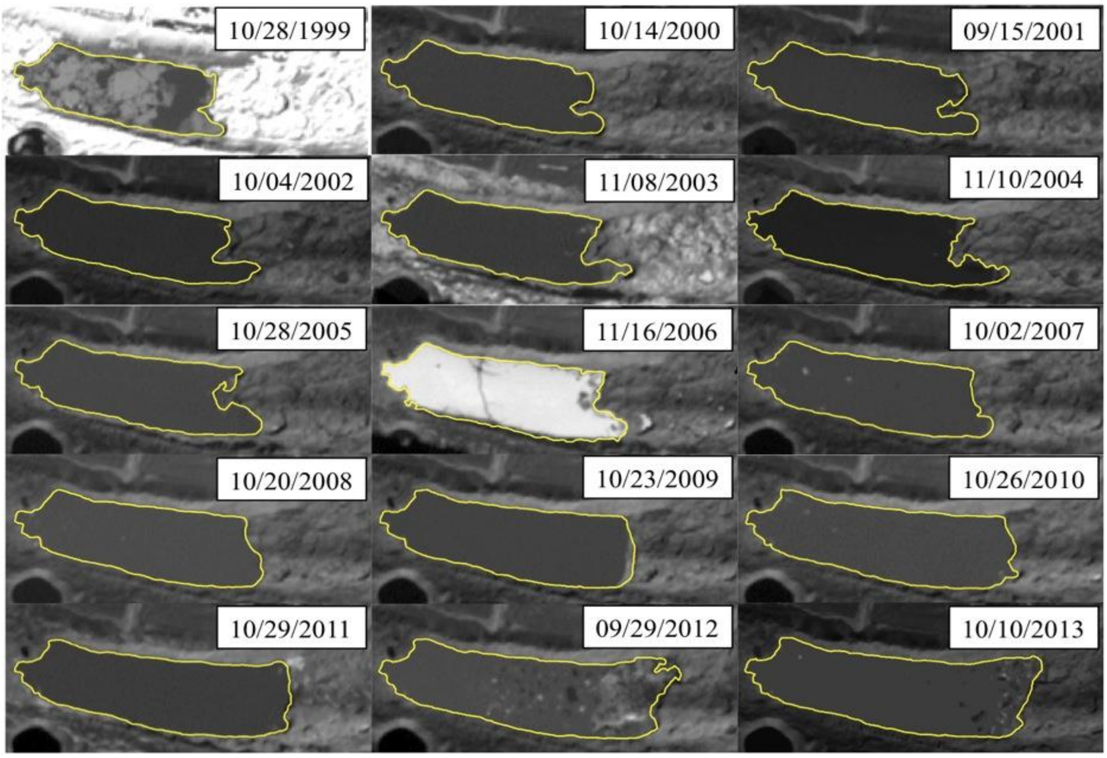


Figure 3.5. shows Imja lake development in the last 15 years (Source Daene McKinney and David 2014)

Chapter Four

4 NEW BATHYMETRIC AND HYDROLOGICAL FIELD SURVEYS OF IMJA LAKE

4.1. Bathymetric field survey of the lake

The specific objectives of this task include

1. To undertake bathymetric assessment to determine storage volume of Imja Lake and estimate volume of water to be drained for lake lowering (at least 3 m) with suitable equipment such as high-performance echo-sounders.
2. To conduct hydrological/glaciological assessment of the Imja Lake
3. To provide hydrological/glaciological inputs to the Survey and Design Thematic Team for the structural design of lake lowering and micro-hydropower project to be designed near the lake. Provide three recommended options for alignment of lake lowering system.
4. Hardware and methods for the survey

Data collection tools and techniques include the following items:

1. 2 Inflatable kayak
2. 3 echosounder
3. 1 side-scan sonar imager (SyQuest Hydrobox Echo Sounder)
4. USV/echosounder
5. 2 Laptop
6. Kayak-mounted instruments
7. Batteries
8. GPS
9. Digital cameras

Echo sonar soundings across the primary Imja Lake were acquired from an inflatable kayak mounted SyQwest Hydrobox sonar sensor. The sonar transducer is powered by a 12v battery and was operated for this survey at 210 kHz (7 mm wavelength). The sensor was mounted to a wooden mast and equipment box that is secured firmly within the kayak **(Error! Reference ource not found.).** Sensor settings for optimal data-return quality included the setting of: sound velocity (based upon cold water temperature and near zero salinity), depth range, gate limits, gains, and ping rate. The sensor was mounted amidships and with ample draft, in our case 25cm, well below the shallow draft of our wide-keeled kayak. For positional control all sonar soundings were paired with precise geographical latitude/ longitude coordinated supplied by a Trimble GeoXH GPS unit with NMEA format outputs.

Figure 4.1: Pictures showing the survey at Amphulapcha lake (left) and Imja lake (right)

USV sonar soundingsacross the western portion of the primary Imja Lake and the first connected small lake west if Imja were acquired with a CEE HydroSystem survey grade CEEPULSE echosounder. The echosounder collected soundings at 1-10 Hz ping rates with matching data output. Data outputs were posted in industry standard NMEA DBT format. Depth and temperature signals are processed inside the sensor and can be displayed on any device that accepts NMEA 0183 or NMEA 2000data. The Control and Communications Module (CCM) installed in the USV receives serial data from a depth sounder and USV-attached GPS and combines all NMEA sentences into a single output stream. Data from both the USV and kayak-mounted echsounders were exported in CSV format and merged.

Prior to commencement of the field survey, an optimal survey grid was designed over the main Imja Lake area; this consisted of an orthogonal set of 23 x 100-m spaced north-south lines, with a set of 4 x 200-meter spaced east-west lines (Figure 4-2); and one longitudinal survey line from the lake terminus to near the glacier calving front. This was the primary survey designed for completion using the kayak-mounted sonar. It was also planned that data were to be collected by the USV-mounted sonar across the western portion of Imja Lake and the two small lakes connected, and just west of the main Imja Lake.

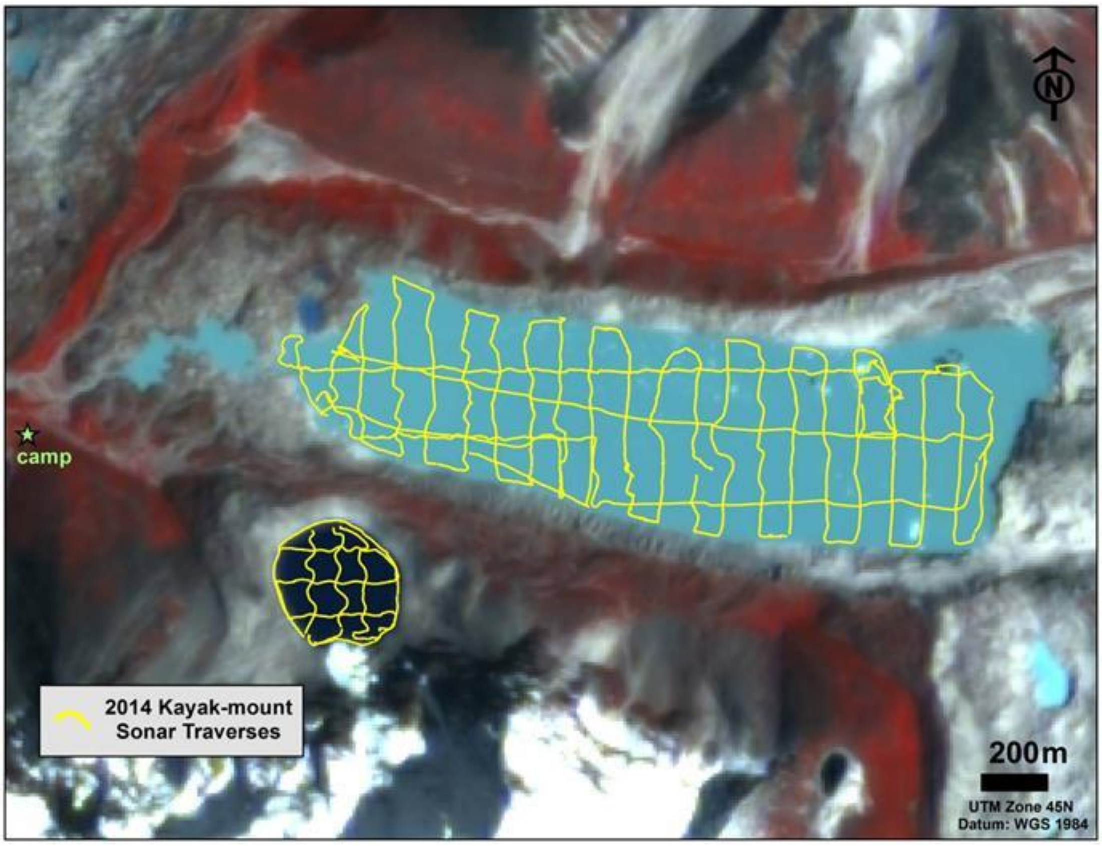
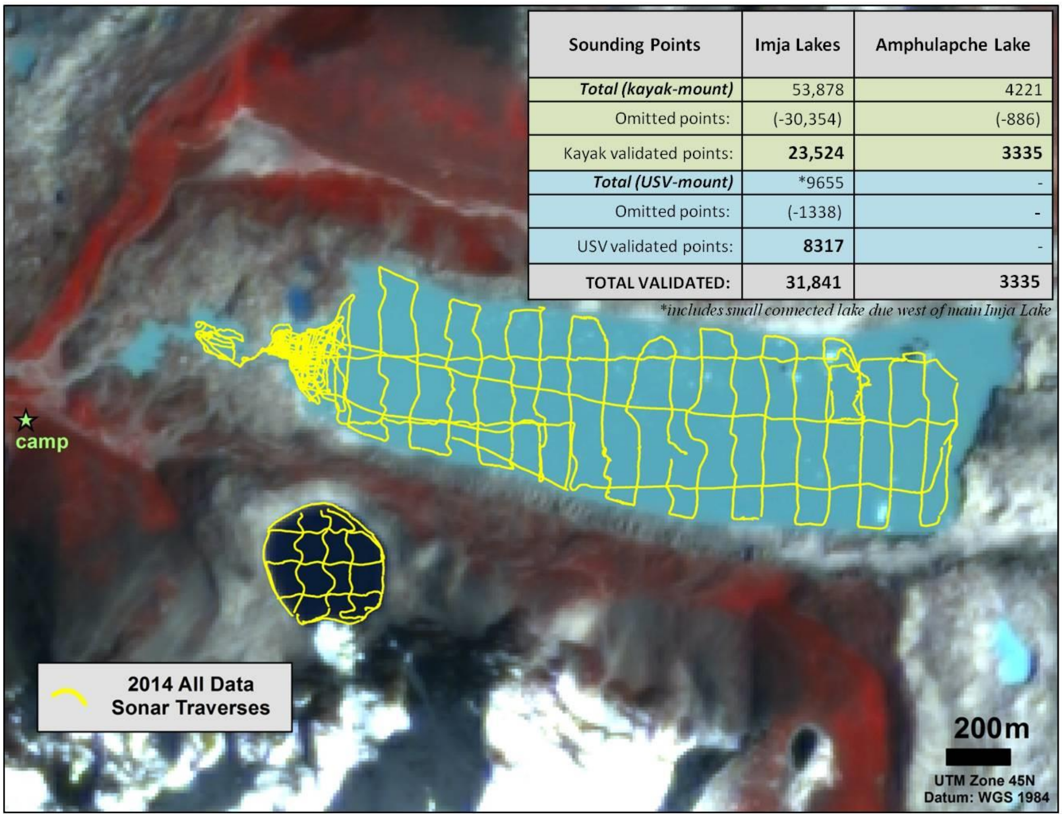


Figure 4.2: An optimal survey grid designed over the main Imja lake area and Amphulapchha glacier lake. Less than 4% of Imja Lake's surface area is more than 50 m away from a trackline, and most of the surface is within 25 m of a trackline. With addition of other datasets (Figure 4-4), roughly 80% of the surface is closer than 25 m to a measurement.

GIS feature shape files were generated for the optimal survey grid lines and posted within the Trimble GPS as an aid to improve navigating and completing the survey efficiently. Subsequently, positioning on the lake and relative to the planned survey were monitored real time. Large icebergs were avoided and therefore some survey lines deviate from the grid. A good portion of the northeastern part of the lake, near the calving front was clogged with large icebergs and could not be accessed. Approximately 22-24 km of survey lines were completed across Imja Lake by the kayak, plus an additional ~4 km across Amphulapcha Lake. A high density of USV tracklines returned abundant data from the far western end of Imja Lake and the easternmost of the two large ponds on the end moraine. The western pond was further covered by a set of plumbline measurements taken through augered holes in lake ice after it became safe to walk on. In addition to thiese data taken in October-November 2014, Somos-Valenzuela, McKinney, and Byers graciously provided their echosounding results from their 2012 survey, which helped greatly in both ponds and added some tracklines in the main lake, thus increasing the point density (Figure 4-4).



Sounding Points	Imja Lakes	Amphulapche Lake
Total (kayak-mount)	53,878	4221
Omitted points:	(-30,354)	(-886)
Kayak validated points:	**23,524**	**3335**
Total (USV-mount)	*9655	-
Omitted points:	(-1338)	-
USV validated points:	**8317**	-
TOTAL VALIDATED:	**31,841**	**3335**

Figure 4.3: Total sonar datea collected during the field work by USV and Kayak mount sonar

4.2. New survey measurements

The kayak-mounted sonar survey amassed 58,099 sounding points including 53,878 for Imja Lake and 4221 across Amphulapche Lake. These soundings have been reduced to 23,524 points and 3335 points respectively. The USV sonar amassed 9655 soundings across the western Imja lakes, which have been reduced to 8317 points. Omitted data points included:

i. Spurious points posting off the survey grid, due primarily to GPS data drop-outs resultant from temporary deteriorating or absent GPS signals.
ii. Spurious sonar sounding data drop outs where depth equals zero.
iii. "Invalid" soundings as classified by Hydrobox sensor processor, or return of zero depth.

iv. Duplicate geographic points resultant from two (likely) sources: a) Data collected at sonar sensor ping frequency >1 sec^{-1}. The GPS only posts on 1 second intervals thereby

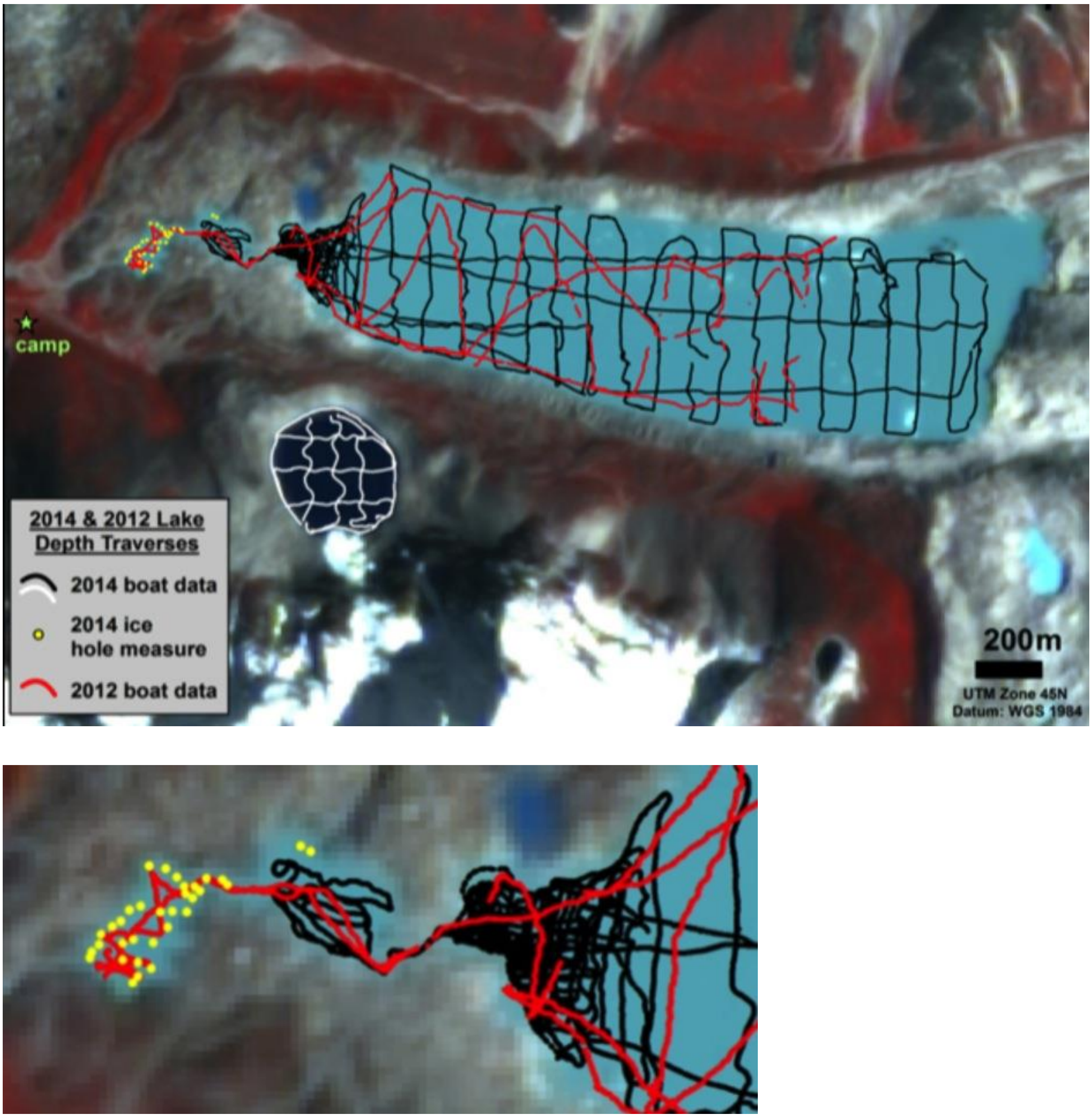


Figure 4.4. All tracklines (valid points only) and other datapoints used in our data analysis. Black = our USV + kayak-borne echoosounder data, red = 2012 echosounder data from Somos-Valenzuela et al. 2014, and yellow dots are our plumbline data taken through augered holes in lake ice.

v. producing quasi-systematic positional duplicates with variable depths; and b) Baud rate incompatibility between GPS hardware cabling (4600 baud) and sonar NMEA required output (9600 baud). This may have generated quasi-systematic clusters of positional duplicate, though variably deep soundings. Below we summarize the total data collection and validation of soundings.

Remaining data points comprise very high density across the lake; from the kayak-mounted sensor are 23,524 soundings; from the USV-mounted sensor and additional 8317, totaling 31,841 soundings. Validated kayak-mounted soundings for Amphulapche lake total 3,335.

These data were applied towards the bathymetric modeling for Imja and Amphulapche Lakes respectively. Since no 'zero depth' data were collected from the outline extent of the lakes, it became necessary to generate lake extents using multispectral satellite imagery. This step served the dual purpose of delineating lake extents and determining lake areas. Fortunately an excellent and very recent image acquired on September 17, 2014 was available from the Earth Observing-1 Advanced Land Imager (EO-1 ALI). An ALI Level 1T image in GeoTIFF format was downloaded which includes radiometric and systematic geometric corrections incorporating ground control points, while employing a 90-meter Digital Elevation Model (DEM) for topographic accuracy. Geodetic accuracy of the product depends on the accuracy of the ground control points and is expected to be within 2 pixels (60m). This image was composited into a bands 654 false-color composite, pansharpened to 10m, and shifted slightly (~15m south) to improve general georeferencing with a series of ASTER imagery.

Table 4.1: Sonar data collection, kayak and USV based platforms

Sounding Points	Imja Lakes	Amphulapche
Total field (kayak-mount)	53878	4221
- spurious (GPS)	-450	-16
- spurious (sonar zero depths)	-	-
- sonar 'invalid' soundings	-121	-62
- positional duplicates	-29783	-808
Kayak-mount valid points:	23524	3335
Total field (USV)	*9655	-
- spurious (GPS)	-1321	-
- spurious (sonar zero depths)	-17	-
- sonar 'invalid' soundings	na	-
- positional duplicates	-	-
USV mount valid points:	8317	-
Total remaining validated points:	31841	3335

To determine lake extents, a normalized difference water index (NDWI) was generated from the ALI imagery. NDWI is computed as: bands [(green - NIR) / (green + NIR)]

The resulting raster was thresholded, with values equal to zero being classified as water, others as land (non-water). The thresholded raster was vectorized into a polygons and manually edited over the ALI pansharpened false-color composite. Areas were then determined from the

finalized lake polygons (one for Imja Lake proper; one for Imja Lake plus the two connected western lakes; and one for Amphulapche Lake).

For bathymetric modeling, zero-valued points are required along the margins of all lakes. Points were generated at 10-m intervals along all lake polylines and assigned depths of zero. These points were appended onto the validated lake bathymetric points to complete the sounding databases for bathymetric modeling. A total of 714 outline 'zero depth' points were added to the Imja Lakes; 127 were added to Amphulapche Lake.

Bathymetric models were interpolated within a GIS project using natural neighbor method. The natural neighbor algorithm finds the closest subset of input samples to a query point and applies weights to them based on proportionate areas to interpolate a value (Sibson 1981). The essential property of this interpolation method is that it's local, using only a subset of samples that surround a query point. Interpolated values are restricted to be within the range of the sample values available within the data set. The algorithm does not 'infer' trends and will not produce peaks, pits, ridges, or valleys that are not already represented by the input sample values. The surface passes through the input samples and is smooth everywhere except at locations of the input samples. The resultant model produced output in geographic coordinates. These raster data were resampled and then posted at 1x1 meter cell dimensions to calculate volume of the lakes.

The hyper-density of USV-based sonar soundings have produced a finely resolved bathymetric model over western Imja Lake and the first small lake due west of the main lake (see PowerPoint slides). However, although the quantity of validated soundings over most of the main lake (collected by the kayak-mount sonar) are more than twice that of the previous survey in 2012 (Somos et al 2014), the resultant bathymetric model appears somewhat coarse over zones of relatively low data density. For this reason we have generated both models of raw data, and a smoothed bathymetric model. The smooth representation was generated by first re-sampling the 1 m resolved model to 10m cell postings, applying a 3x3 cell low-pass filter, and re-sampling back down to 1m cells. This had the effect of strongly dampening the high frequency features observed on the modeling of raw (unsmooth) data. Nevertheless, artifacts are still visible.

4.3. Field photos from the bathymetry survey

Below, Figures 4-5 and 4-6 includes some of the pictures taken during the field survey period, which visually shows the physical and weather condition at the Imja site.

Figure 4.5. Photos shows how the USV boat was used in the lake to collect the data, person standing on the moraine is using the remote control to control the directions and the speed of the unmanned boat.

Figure 4.6. Photos showing the deployment of the kayak and its echosounder.

4.4. Hydrological field survey

4.4.1. Meteorology, climate, and weather records

The temperature of Imja Lake was calculated from the Dingboche weather data and the normal lapse rate of about 5.7 K/1000 m (or 4° C temperature depression for the 700 m difference in elevation of the two places), which is intermediate between a dry and wet adiabat. There is no significant linear temperature trend, although there may be a significant oscillation of one half cycle with a period 28 years.

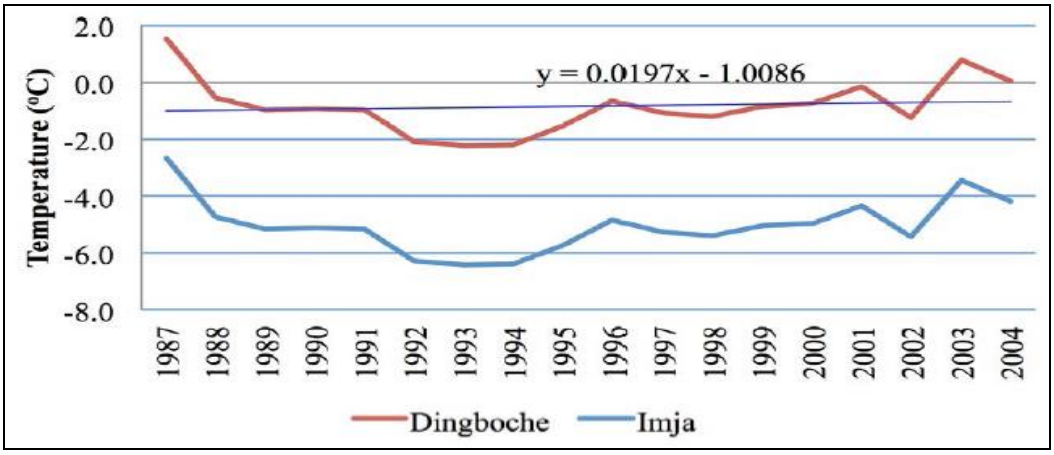


Figure 4.7. Mean annual temperature from 1978 to 2004 at Dingboche (red line) and Imja Lake (blue line).

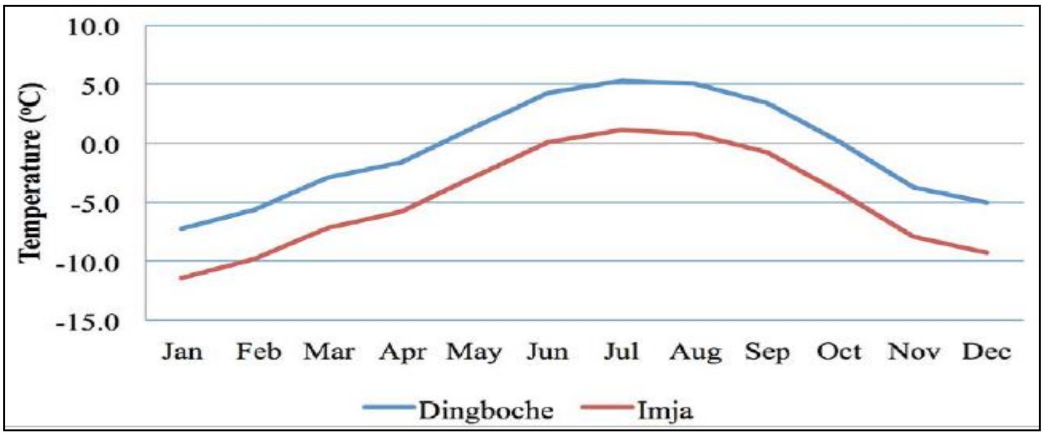


Figure 4.8. Mean monthly temperature at Imja Lake obtained from Dingboche temperature records from 1987 to 2004.

Mean annual precipitation was recorded from 1978 to 2004 at Dingboche. We have deleted years where data gaps are excessive. Precipitation varies considerably from year to year. A slight drying trend might appearto exist but it is not statistically significant. Dingboche (and Imja Lake) are semi-arid as indicated by mean annual precipitation near 390 mm.

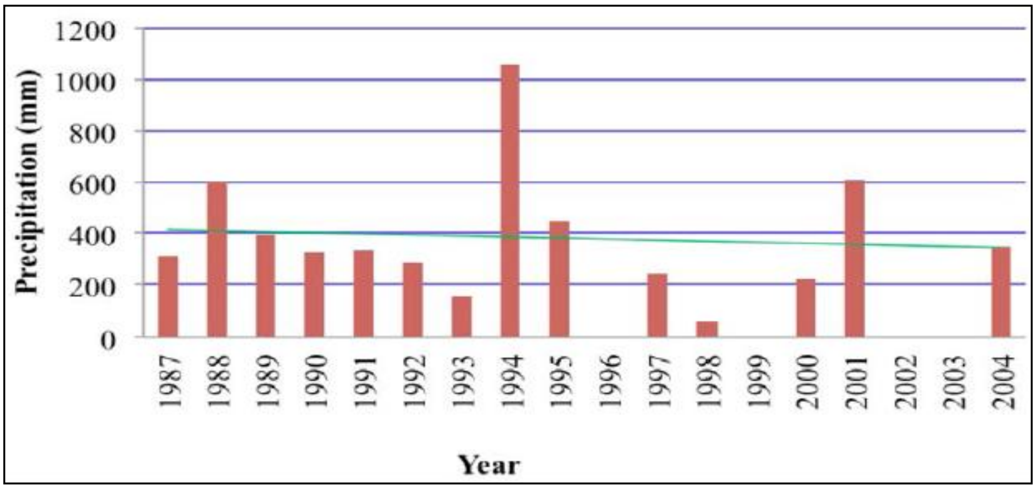


Figure 4.9. Mean annual precipitation from 1978 to 2004 at Dingboche.

Mean monthly precipitation was obtained from a record spanning from 1987 to 2004. The glaciers are summer-accumulation types. They would not exist without summer snow. ASTER imaging shows that snow avalanches might be major components of accumulation. Dingboche (and Imja Lake) have a strong monsoonal precipitation signature.

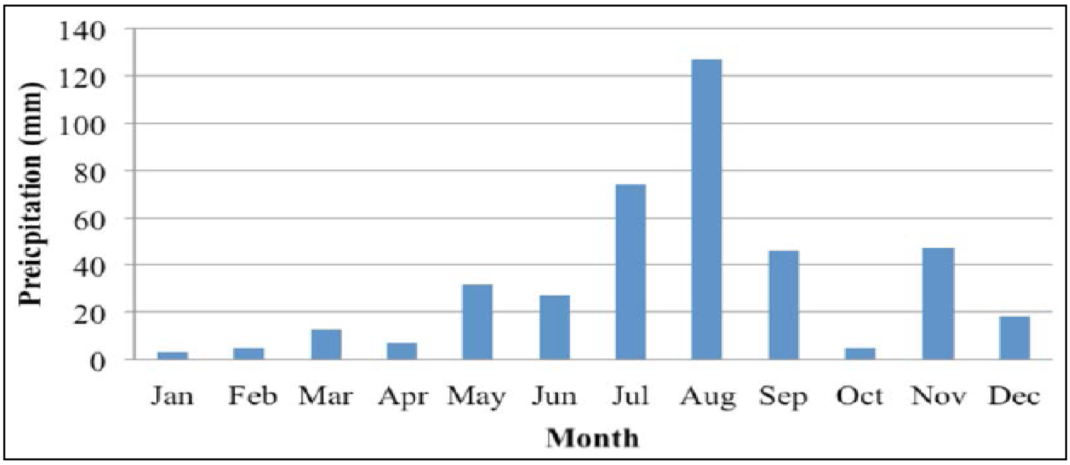


Figure 4.10. Mean monthly precipitation obtained from records spanning from 1987 to 2004.

Stream discharge of Imja Khola decreased sharply from 1988 to 2004. The trend in fact is striking. Obviously there have been major changes in the system, but deducing what changes were responsible is a challenge. Precipitation may have decreased (but the direct precipitation record does not show such a strong drying trend), cloud cover may have increased (though we lack data for it) and with it glacier melting may have decreased, annual temperatures may have decreased (though the temperature record does not indicate cooling), summers may have cooled and thus meltwater was reduced, or more meltwater may have been stored somewhere in the Dingboche Basin; or any combination. Because most of the region is permafrost, small changes in summer temperatures can cause large changes in melting; furthermore, meltwater can fill voids in glaciers or it may refreeze in the glaciers and thus may be stored, or if temperatures warm,

meltwater can be released from permafrost. Furthermore, water flow through Imja Khola may include a component of subsurface flow through alluvial gravels and boulders, such that small differences in meltwater throughput may be manifested in large changes in above-surface flow. In fact, the possibility that subsurface flow is an unmeasured but important component of total discharge could impact our hydrological analysis. Thus, there is no shortage of mechanisms that can cause discharge to fluctuate, but identifying the right combination of mechanisms is a challenge beyond the available data to resolve.

Mean annual discharge of Imja River at Dingboche hydrological station is not in close coherence with the annual precipitation data for the station. Glacier melting may contribute to this trend if thinning and retreat have decreased for whatever unknown reasons, such that glacier melting may help explain the disconnection to precipitation. We note that with such high glacierization, and occurrence of extensive snowfields in many non-glacier areas through much of the year, it is to be expected that there would not be strong coherence with precipitation. Another possibility is that the precipitation data at the Dingboche locale are not representative of precipitation in the whole basin. We note that there is wide variation in the fluctuations of river hydrographs and precipitation records among various Nepal stations, clearly indicating the strong influences of microclimates and differential glacierization. Even within the Dingboche Basin we may expect some variability. However, lacking the data needed to make a reliable assessment of how Imja Basin may differ from Dingboche Basin, our analytical approach is simply to scale glacier melt and precipitation runoff to basin area, implicitly assuming that the two basins are representative of one another.

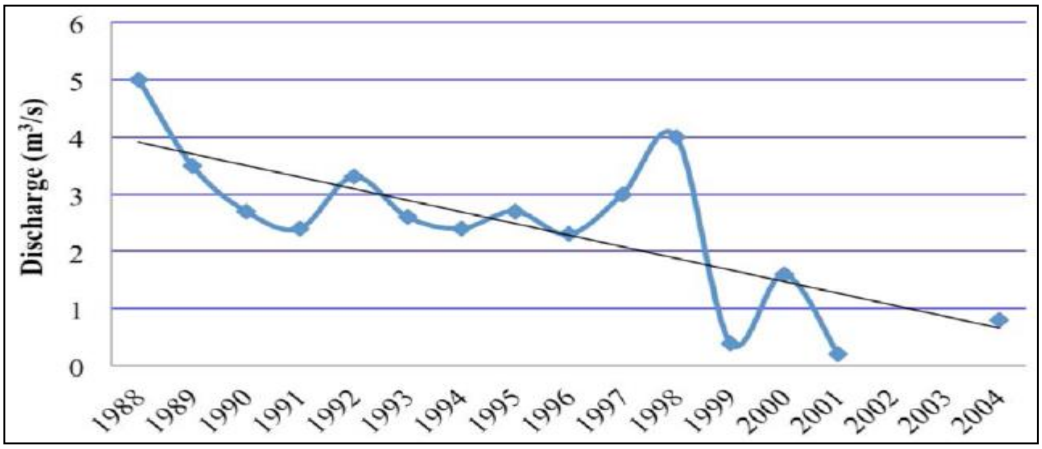


Figure 4-11. Mean annual discharge of Imja River at Dingboche hydrological station from 1988 to 2004

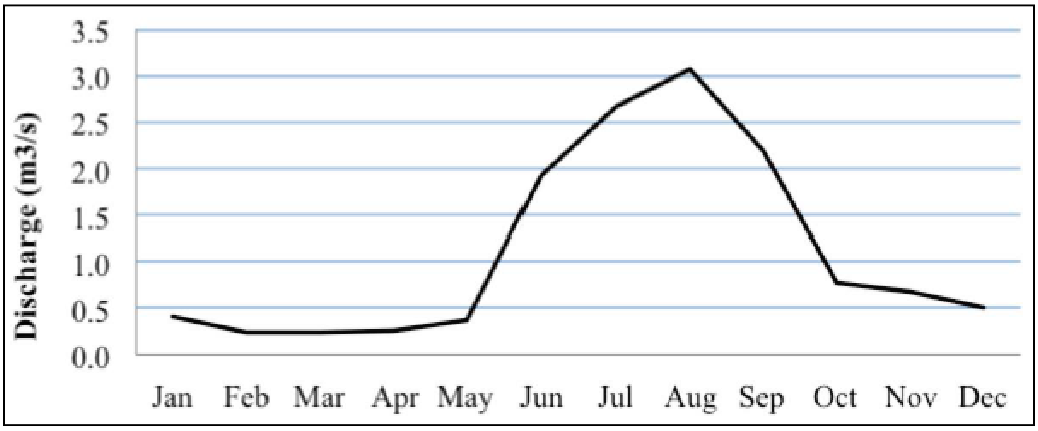


Figure 4-12. Annual hydrograph of Imja River (Imja Lake outlet) based on a model constrained by measured value for May 2009 by ICIMOD, September 2012 by Somos and October 2014. NOTE: in our further analysis below we have used simple basin-area scaling to extend Dingboche Basin data to Imja Basin in place of this more elaborate, but not necessarily more accurate, approach.

4.4.2. In situ hydrological measurements (Oct 2014)

Discharge measurements were carried out in Imja River at a site near the outlet of Imja Lake from 17 October to 22 October, 2014. Two methods were applied to measure the discharge: 1) Constant tracer injection method, and 2) Salt dilution method.

A total of 12 measurements were carried out at Imja River near the outlet of Imja Lake (11 measurements) and at Dingboche hydrological station (1 measurement). At Imja Lake outlet 9 measurements were carried out by using the constant tracer injection method and 2 by using the salt dilution method. Further, a stream gauge was installed to observe the gauge height of water level in Imja River.

4.4.2.1. Stream flow, Imja Khola

Constant tracer injection method:

This method uses fluorescent dye tracers (rhodamine), which is injected at a constant rate at a fixed point of the river. The salient analytical equation used for the analysis is:

$$Q = q.\frac{C_1}{C_2} \ [l/s] \qquad (1)$$

Q = Discharge quantity [l/s]

q = Constant rate injection volume of tracer [l/s]

C_1 = Concentration of injected solution [µg/l]

C_2 = Tracer concentration in the sampling cross-section [µg/l]

A precisely measured quantity of initial solution with a concentration of C_1 is injected into the water by a Mariotte Bottle over a specific period of time. The injection time must be calculated such that an evenly diluted concentration C_2 flows through the entire sample cross-section during a specific period. If C_0 is very small, and q compared with Q is negligible, the background concentration of the injected tracer low, the discharge can be calculated byequation 1.

4.4.2.2. Salt dilution method:

This method is employed to estimate the discharge in Imja River near outlet of Imja Lake. This method includes injection of common salt at fixed point of river and measure the salt concentration or conductivity using a conductivity meter.

4.4.2.3. Seepage through the end moraine

To find out the seepage from the lake, experiment was carried out using fluorescent dye. Dye is injected in the lake at two sites using 50 g of dye (30 and 20 g). The time of dye injection is 11:30, on 22 October 2014. Then, samples were taken in different times after injection. 18 samples were taken from five different site over two days. Two samples detected seepage.

4.4.2.4. Physical/Chemical hydrological properties

Physical properties of river water were observed during the field period. The physical parameters include the pH, electrical conductivity (EC) and total dissolved solids (TDS), and suspended solids. These parameters were measured twice a daily during field period. The variation of water levels in the Imja river were observed and measured with gauge height from the guage station at Imja river outlet near the bridge.The values of discharge obtained after laboratory analysis are presented in Table 4-4. A few more samples are being analyzed in the DHM laboratory.

Figure 4.11*: *Tracer Injection at Imja river

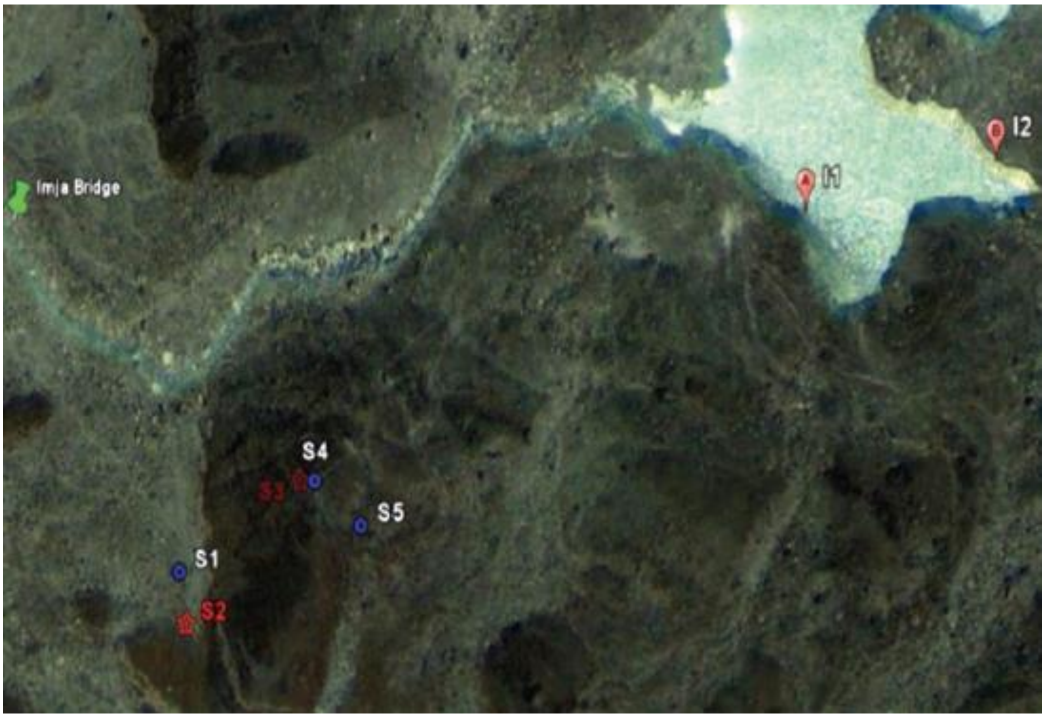


Figure 4.12. Location of dye injection points (I1 & I2), sampling points for seepage test (S1, S2, S3, S4, and S5) and points (star shape) with red color shows the seepage detection points (S2 and S3).

Table 4.2. Results of dye tests of seepage

Sample ID		Date	Sampling Time	Concentration mg/l	Remarks
	Fresh water	21-Oct-14	1:00	-1.8	Fresh Water
	Fresh water	22-Oct-14	2:00	-5.3	Fresh Water
S1	Near to Base camp	22-Oct-14	13:20	-9.3	No seepage
S2	Near to Base camp	22-Oct-14	1:20 PM	-9.5	No seepage
S3	Amphulapcha side	22-Oct-14	1:20 PM	-13.1	No seepage
S4	Amphulapcha side	22-Oct-14	1:20 PM	-13.1	No seepage
S1	Near to Base camp	22-Oct-14	5:00 PM	-11.3	No seepage
S2	Near to Base camp	22-Oct-14	5:00 PM	-13.3	No seepage
S3	Amphulapcha side	22-Oct-14	5:00 PM	7.4	Seepage
S4	Amphulapcha side	22-Oct-14	5:00 PM	-11.9	No seepage
S5	Amphulapcha side	22-Oct-14	5:00 PM	-13.6	No seepage
S1	Near to Base camp	23-Oct-14	8:00 AM	-10.6	No seepage
S2	Near to Base camp	23-Oct-14	8:00 AM	-13.0	No seepage
S3	Amphulapcha side	23-Oct-14	8:00 AM	-11.1	No seepage
S4	Amphulapcha side	23-Oct-14	8:00 AM	-10.7	No seepage
S1	Near to Base camp	23-Oct-14	2:00 PM	-13.3	No seepage
S2	Near to Base camp	23-Oct-14	2:00 PM	5.3	Seepage
S5	Amphulapcha side	23-Oct-14	2:00 PM	-11.1	No seepage
S4	Amphulapcha side	23-Oct-14	2:00 PM	-10.1	No seepage
S3	Amphulapcha side	23-Oct-14	2:00 PM	-13.0	No seepage

Table 4.3: Imja river at outlet of Imja lake

Date	Time	Discharge (m^3/s)
17 October, 2014	11:00 AM	0.768
17 October, 2014	4:00 PM	0.892
19 October, 2014	9:30 AM	0.529
20 October, 2014	10:00 AM	0.550

Average discharge of Imja Khola was 0.685 m^3/sfrom 17 October to 20 October 2014 and 2.614 m^3/sat Dingboche on 15 October 2014 at 11:30 AM. The value of discharge in Imja River near the outlet of Imja Lake was intermediate between discharge values during the month of May, 2009 measured by ICIMOD (0.400m^3/s) and August 2012 (1.026 m^3/s) measured by Kathmandu University. Although it is only one measurement, we note that the simultaneous Imja River

discharge at the outlet of Imja Lake and at Dingboche was 0.262 by our measurements, which is close to the area ratio (0.28) of Imja to Dingboche basins.

The water samples were collected for the testing of physical characteristics of water from Imja river. The average value of pH, conductivity and total dissolved solids are shown in Table 4-5.

Table 4.4: Physical characteristics of Imja River

Parameter	Value
pH	8.17
Electrical conductivity (EC)	17 µS/cm
Total dissolved solids (TDS)	8 ppm
Total suspended load	0.193 g/l

4.4.2.5. Discharge Measurement Results

The field measurement for the discharge at different locations, time and date are presented in Table 4-6.

Table 4.5 Results of the discharge measurements during site visit

S.No	Place/ Station	Date	Time	Gauge height	Discharge (m^3/s)	Remarks
1	Dingboche/Imja river	15-Oct-14	12:15	1.13 m	2.61	
2	Outlet of Imja Lake	17-Oct	16:00	0.20	0.892	snow fall
3	Outlet of Imja Lake	17-Oct	11:00	0.18	0.768	
4	Outlet of Imja Lake	18-Oct	10:00	0.17	0.830	
5	Outlet of Imja Lake	19-Oct	14:45	0.19	0.920	snow melting
6	Outlet of Imja Lake	19-Oct	10:15	0.16	0.529	
7	Outlet of Imja Lake	20-Oct-14	9:40	0.16	0.550	
8	Outlet of Imja Lake	20-Oct-14	16:00	0.18	0.864	
9	Out let of lake	21-Oct-14	10:15	0.17	0.790	
10	Out let of lake	22-Oct-14	9:15	0.18	0.870	snow melting

4.4.2.6. Total suspended load: Suspended load is important in hydropower design. The average sediment load of the Imja River near the outlet of the lake is 193 mg/l. Sediment load of the Imja River at outlet is 11.4 metric tons per day based on measured average discharge from 17 October to 22 October 2014.

Chapter Five

5 BATHYMETRY RESULTS, VOLUMETRIC DATA ANALYSIS AND GROWTH OF IMJA LAKE

5.1. Volumetric summary

Volume of water within the Imja and Amphulapcha lake is estimated from the Bathymetric data analysis. The result of present study revealed that maximum recorded depth of the lake is 149.8 m from the surface, whereas the area of the lake was 1.28 km^2 and total volume of the water within Imja Lake (Primary) is 75,217,000m^3(Table 5.1). The maximum measured depth of the lake is greater than the 116 m measured in 2012 by Somos-Valenzuela et al. (2014).Similarly, our 2014 measured volume of the lake also greater than 61.7 million m^3 measured in 2012 by Somos-Valenzuela et al. (2014). Key differences between our 2014 survey and the 2012 survey is that the present study has found that the lake continues to deepen eastward through the eastern third of the lake that was not surveyed in 2012. Somos-Valenzuela et al. (2014) had assumed that the lake becomes shallower in that previously un-surveyed region. Survey overlaps with Somos et al. indicate that lake depths and major features of the bottom relief are very similar, though we have provided a higher density of data. We have not yet performed a detailed comparison of track line crossing points of the two surveys, a task which is planned but falls beyond the scope of this present study.

The eastern (upper) of two ponds developed along the spillway on the end moraine attains up to 18 m depth. The 2012 and 2014 studies provided similar results for this pond.

Amphulapcha Lake has maximum measured depth of 68.2 m with volume of 3.2 million m^3. Sampling density is low, but enough to gather rough estimations.

Some graphical outputs of bathymetric data are shown in Figures 5-1 to 5-5. Further data and high-resolution versions of these results are given in Appendix 1.

Some bathymetric survey data

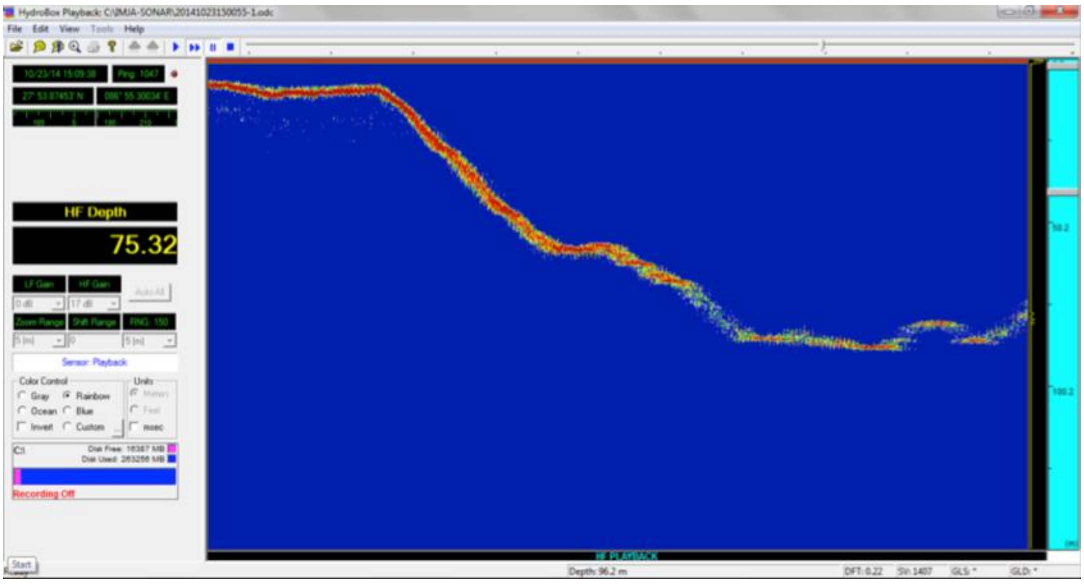


Figure 5.1. Sample of Hydrobox echosounder data in Imja Lake. In places, more complex echo returns are produced, including some profiles that reveal sub-bottom structure, and others that indicate sonar scattering off large boulders.

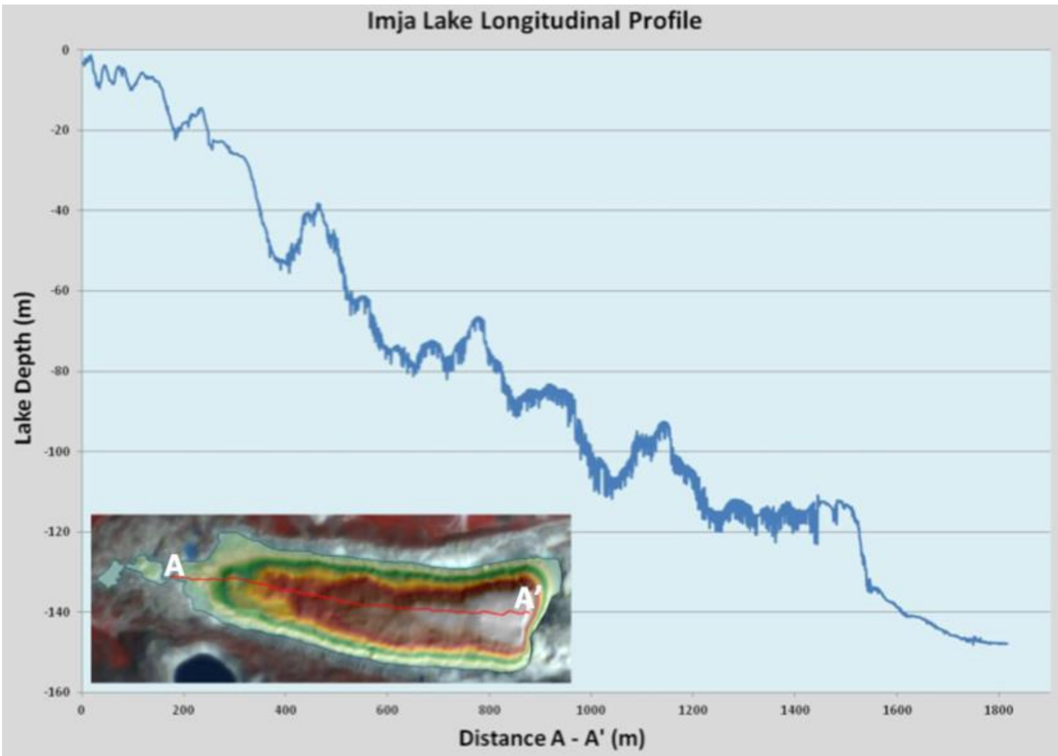


Figure 5.2. Longitudinal depth profile of Imja Lake. The 10-20 m amplitude ridges superposed on the eastward-deepening profile may be a series of end moraines or rock falls or other structures.

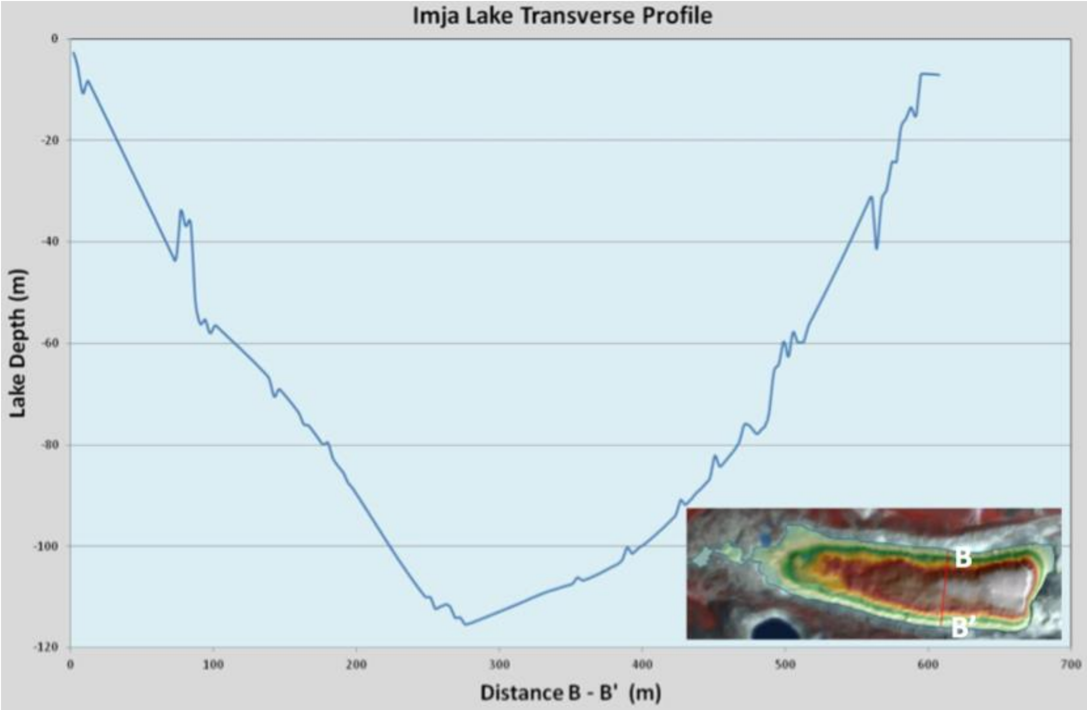


Figure 5.3. Transverse profile line. The V shape is suggestive of sediment infilling of what was once probably a U-shaped glacial valley.

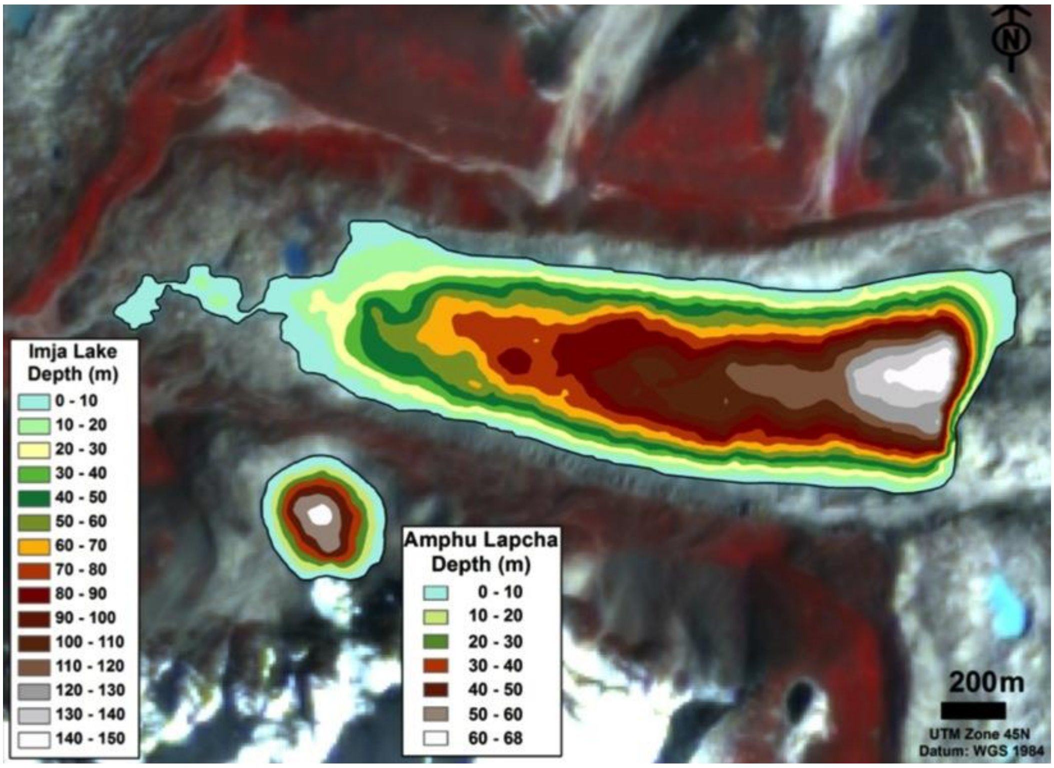


Figure 5.4. Bathymetric contour map of the lake superposed on a satellite base image.

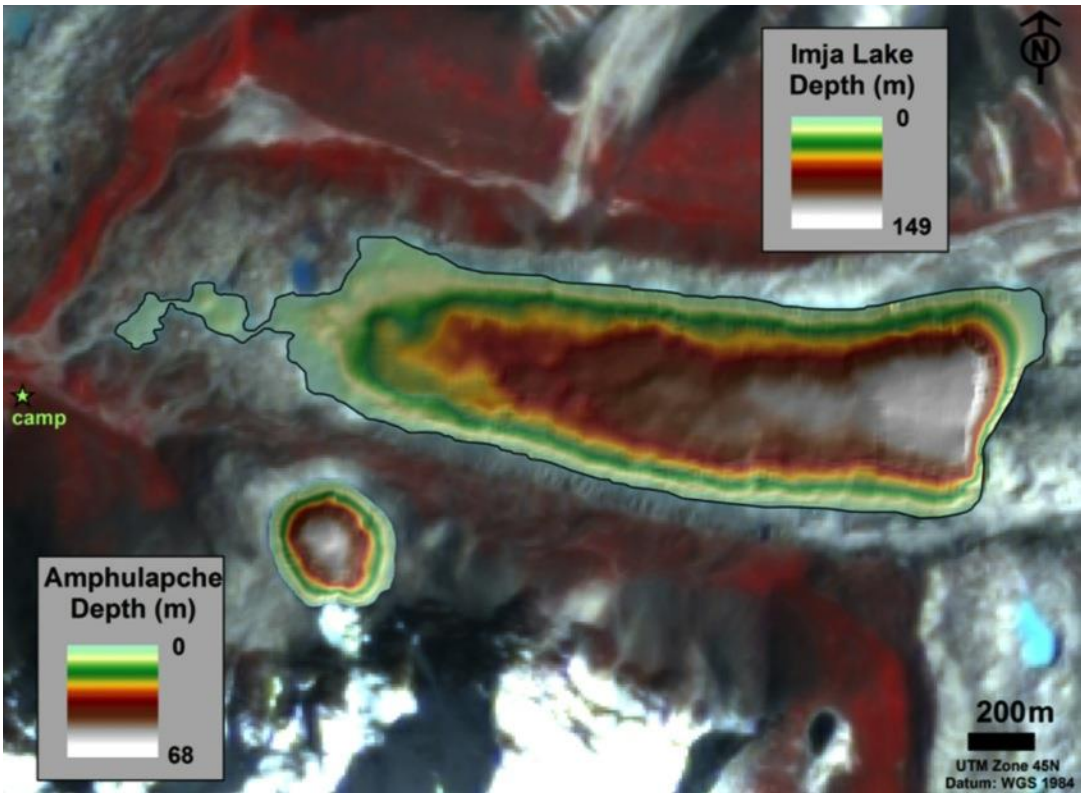


Figure 5.5. Smoothed bathymetric contour map draped onto a smoothed hillshade of bottom topography, all placed onto a satellite base image.

5.2. Area growth history of Imja Lake

The area growth history of Imja Lake is very well known and can be fit by a second-order polynomial. The polynomial extrapolation may provide a guide to the future growth for the next several years (Fig. 5-6), though we do not recommend extrapolation beyond 2020 or 2025, as the growth trend may diverge from the polynomial if the valley bottom topography changes slope as the lake lengthens.

Some of the scatter of measured lake areas around the polynomial shown in Figure 5-6 must be due to measurement error. However, we have noted that some satellite images in the time series show brief re-expansions of the glacier and contractions of the lake, so we have solid reason to suspect that a component of oscillation exists superposed on the polynomial growth trend. Seasonal fluctuation can be modeled on

Table 5.1. Summary of the area, perimeter, maximum depth and volume of Imja Lake (Primary), Imja Lake complex, and Amphulapche Lake

Parameter	Imja Lake (primary)	*Imja Lakes	Amphulapche Lake
Area (km^2)	1.28	1.32	0.12
Perimeter (km)	5.776	7.139	1.265
Max depth (m)	149.8	149.8	68.2
Volume (m^3)	75,217,056	75,364,959	3,197,641

*Includes Imja Lake proper plus first connected lake adjacent and due west of Imja. Does not include volume from the western-most small lake; no 2014 field data have been collected for this lake.

top of the 2nd order polynomial fit to the whole dataset. Arguably, the seasonal fluctuating component may be a sinusoid, so we multiply the best-fit polynomial by

$(1+0.075*\sin(2*(\pi)*(\text{Year}-1960.4)))$,

where the argument of the sine function is in radians keyed to the annual cycle, and the year is in decimals. For instance, the midyear of 2010 (approx. July 1) is represented as 2010.50. The polynomial and sine function explain some of the variation, though we note the issues of error bar sizes and lack of errors bars for 3 points, and one point that doesn't fit at all. Amplitude variation due to the sine function is consistent with 60 W/m^2 of added summer insolation absorbed by the lake. Added for half the year to the whole lake at 2014's size, this heat can melt 60 m thick of ice across an area 500 m x 150 m.

However we cannot know what the actual volume and maximum-depth growth histories have been (Fig. 5-9). All estimates are probably underestimates because of sampling issues. However, we think our present estimate is close to correct because our sampling was high. We do not think that the changes between measurements are significant: they probably reflect under sampling as well as actual volume increase. So, it is difficult to make a well constrained growth history of Imja Lake in terms of the actual volume and depth.

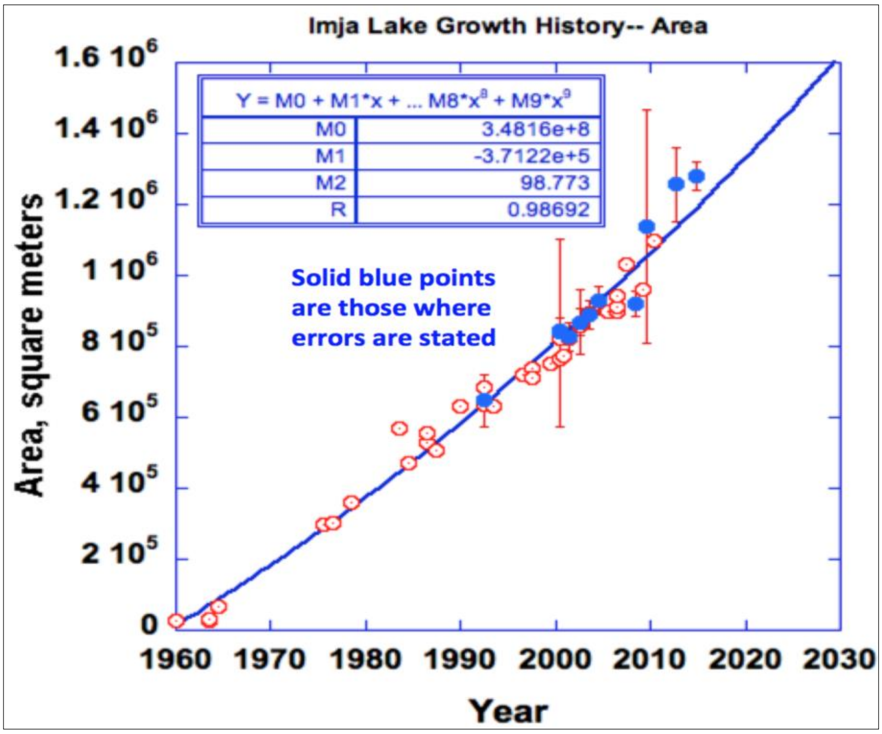


Figure 5.6. Imja lake growth history Solid blue points indicate the points where errors are stated.

The polynomial is a best fit and has been projected to year 2030. See Appendix 1 (CD) for higher resolution graphics.

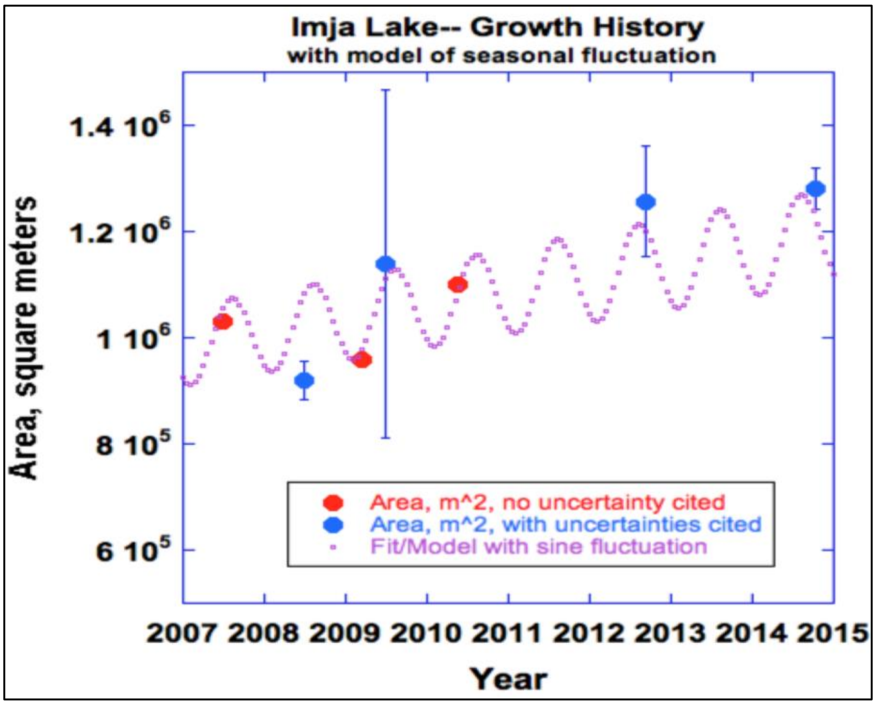


Figure 5.7. Recent growth history of Imja Lake fit with the same polynomial as in Figure 5-6 and with an added sine wave fluctuation to represent hypothesized seasonal variability. See Appendix 1 for higher resolution graphics.

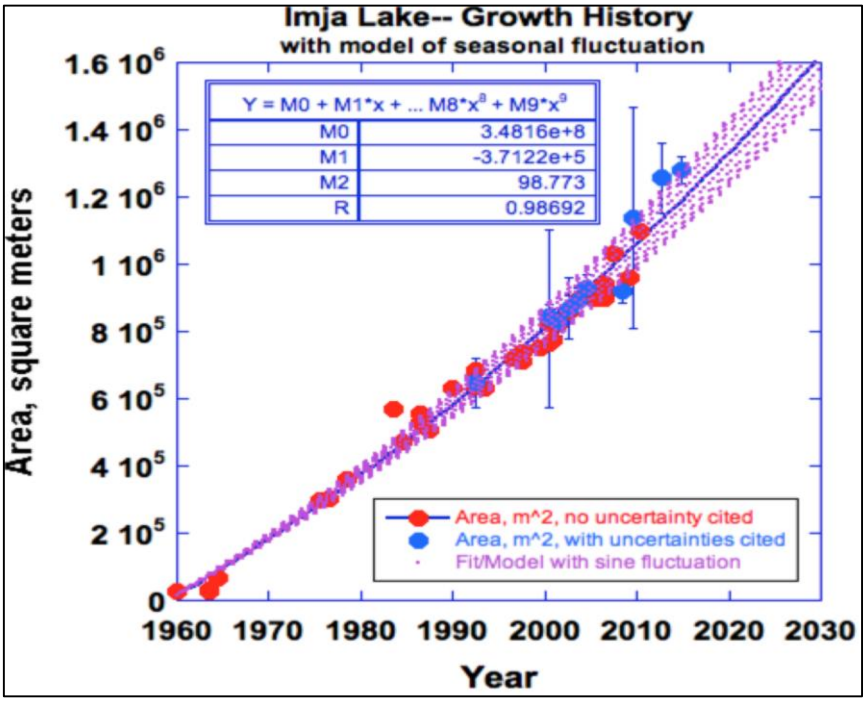


Figure 5.8. Same as Figure 5-7 but the growth history is represented back to the initiation of Imja Lake and is projected forward to 2030. See Appendix 1 for higher resolution graphics.

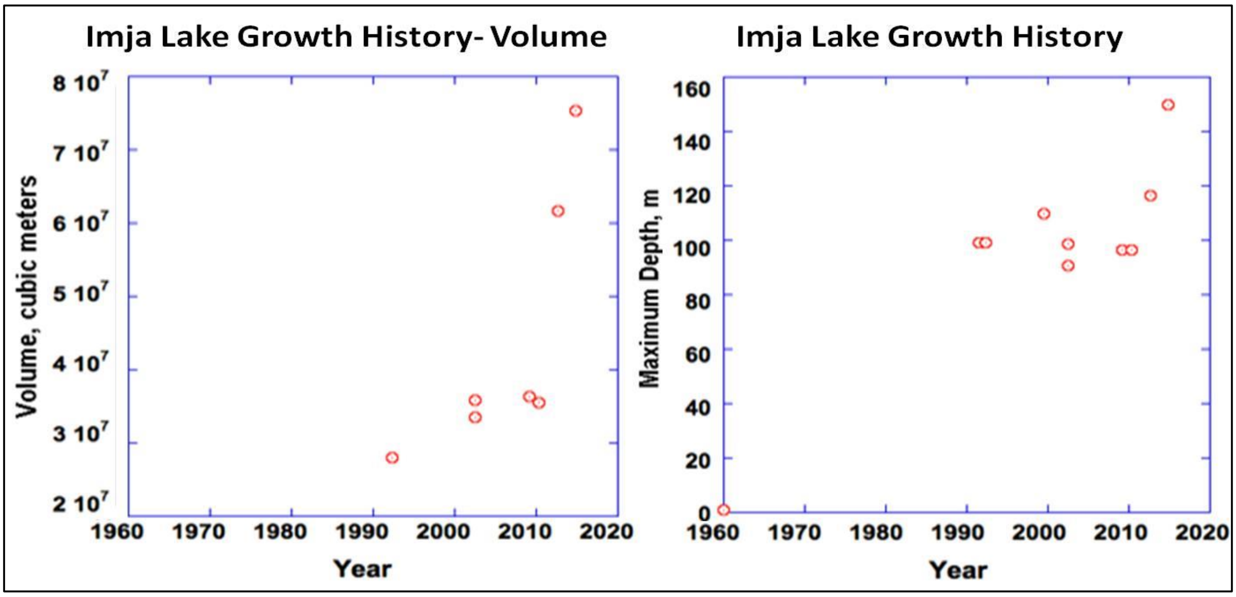


Figure 5.9. Imja lake history in terms of volume (left hand side) and maximum depth (Right hand side). The data do not define grwoth trends but rather some unknown combination of growth and increasingly complete spatial sampling of the lake.

5.3. Rate of shore retreat

By far most of the change in lake area is due to calving retreat (and brief readvances) of the glacier terminus. However, the moraine-bound shorelines are also changing, though much more slowly. In Figure 5.10 we show the change in lake shorelines between ASTER images acquired on December 20, 2001 and January 6, 2008 (interval of 6.05 years). Since the images were acquired at almost anniversary dates and were also acquired close to the winter solstice, the sun angle barely changed between these images; hence, shadows are almost identical, thus facilitating an accurate analysis. After coregistering the images, the shoreline was demarked by using a thresholded ASTER Band1/Band3 ratio with careful manual inspection to assure adequate threshhold values.

Figure 5.10 shows the results of the shoreline mapping. It is apparent that the 2011 and 2008 images have shorelines of the main lake that mostly lie on top of one another, but there was a substantial expansion of the ponds on the damming end moraine. Some measured attributes of the shorelines are as follow:

MAIN LAKE (with arbitrary east-end cut-off to avoid the calving terminus):

2001: lake shoreline (minus the cut-off line) = 4266 m

2008: lake shoreline (again, minus the cut off line) = 4288 m

2001: lake area (minus the eastern cut-off area) = 0.7270 km^2

2008: lake area (with same east-end cut-off) = 0.7378 km^2

TERMINAL PONDS:

2001: ponds shoreline = 1350 m

2008: ponds shoreline = 1620 m

2001: ponds area = 0.0151 km^2

2008: ponds area = 0.0270 km^2

For the main lake, since the fractional change in area and perimeter was small, the differential analysis gives shore retreat as simply the change in lake area divided by the mean perimeter of

the lake, i.e., 2.53 m mean shore retreat during the 6.05-year interval, or a rate of 0.42 m/year. By reference to Figure 5.10, one may see that the change in the shoreline is probably significant at only a few small locations and that for the most part of the shoreline has not undergone a measurably significant change. We estimate the error and suggest that the mean shore retreat is 0.4 ±0.6 m per year, i.e., wthin range of no change at all.

The ponds show a clearly significant growth. Because the fractional change in area is almost a factor of two, and furthermore, since there were initially four ponds we need a different approach to assess mean shore retreat. As an approximation to get a single metric of shore retreat rate of the ponds, we consider there to be four ponds of equal area and assess their mean radii if approximated as circles. Analyzed this way, we find that the ponds' radii increased by a mean value of 11.7 m over the 6.05-year interval, or about 1.9 m/year. The uncertainty may again be as estimated from the analysis of the main lake, so we assess the mean retreat rate of the ponds' shoreline to be 1.9 ±0.6 m/year. By reference to Figure 5.10, there are clearly places where the shore has not measureably changed and other shoreline stretches

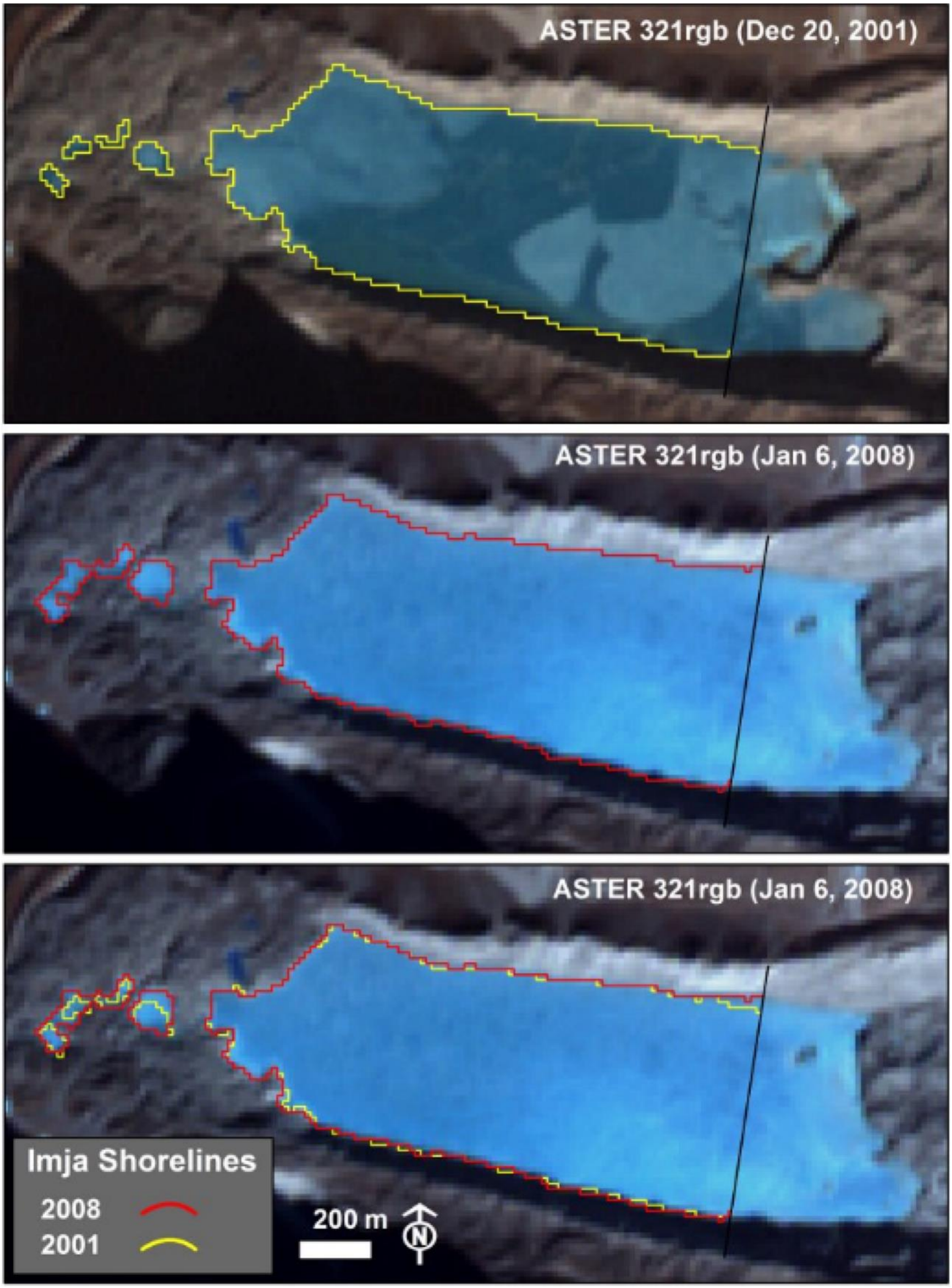


Figure 5.10. Assessment of lake shore changes west of the area of glacier frontal variations.

where the change was more than the average amount. Near the outlet, the lowermost pond

grew during the interval between images, but possibly by less than the average amount, so perhaps shore retreat was somewhere around 1m/year.

Aside from the major changes at the glacier terminus, four other sets of processes may change the location of the shore and the area and perimeter of the lake and the advance or retreat of the shore. This is true for the ponds on the end moraine as well as for the main lake. Of the following four processes, the first two listed are happening and are important, the third happens but is minor, and the fourth is uncertain whether it happens but it could be important.

(1) Mass wasting and erosion (rockfalls and rock topples; dry sediment flows; gully erosion due to runoff and debris flows; and gelifluction and solifluction creep and general colluvium creep due to freeze-thaw, saturated sediment flow, and wetting/drying).
(2) Melting of ground ice (periglacial ice or buried dead glacier ice) and consequent slumping of the debris-covered surface.
(3) Fluctuations of lake level due to changes in the outlet geometry and variations of water influx and discharge.
(4) Glacier-like residual creep of buried ground ice or major slumping into the lake.

In general, the first two processes will tend to expand the lake and cause shorelines to retreat outward from the lake, although a rockfall, if deposited at the water's edge, may cause the shore to advance locally into the lake. Mass wasting and erosion probably dominates shore changes of the main lake outside the area of the glacier front fluctuations. On the end moraine, we guess that the ponds' growth is mainly by melting of ground ice. Assuming typical 20-degree slopes of the terrain near the shore, the mean 1.9 m shoreline retreat could be caused by 70 cm of surface lowering due to ground-ice thaw. This is not an implausible value. The lake level generally oscillates seasonally by about 50 cm amplitude, and this may cause typically 1.4 m range (±0.7 m around the mean shore position) of oscillating advance and retreat of the shoreline, i.e, not much in comparison to the mean 11.7 m shoreline retreat that we measured. The fourth process has the potential of tending to close up the lake and hence shift shorelines into the lake, but so far the evidence indicates that this is not the major process causing shoreline changes.

5.4. Effect of lake lowering on lake volume

Bathymetric data of the Imja Lake are analysed to understand the effect of lake level lowering. The results are very similar to Somos et al., the small difference partly being ~2% increased lake area, e.g., 11 million cubic meter reduction for 9 m lake lowering (Somos et al. 10.6 million) 22.9 million cubic meters for 20 m reduction (Somos et al. 21.7 million). Similarly, if we decrease the water level by 3 meters the volume of the lake will be 71.5 million cubic meters with area of 1.25 m^2 (Fig. 5-11). However, this is referenced to the present lake dimensions; the lake no doubt will grow more voluminous if due just to lengthening.

Imja Lake area and volume with decreasing lake levels		
Decreasing Lake Level (m)	Area (km^2)	Volume (m3)
0	1.31	75,364,959
-1	1.28	74,076,585
-2	1.26	72,802,937
-3	1.25	71,546,903
-4	1.23	70,308,404
-5	1.21	69,087,657
-6	1.20	67,883,910
-7	1.18	66,695,433
-8	1.17	65,519,921
-9	1.16	64,357,383
-10	1.14	63,208,662
-15	1.08	57,653,283
-20	1.02	52,417,698
-25	0.96	47,481,252
-30	0.91	42,800,523
-35	0.87	38,351,084
-40	0.82	34,131,085
-45	0.78	30,140,899
-50	0.72	26,401,189
-55	0.66	22,954,226
-60	0.61	19,782,872
-65	0.55	16,879,219
-70	0.50	14,227,700
-75	0.44	11,863,673
-80	0.39	9,776,132
-85	0.34	7,956,241
-90	0.29	6,387,442
-95	0.26	5,001,111
-100	0.22	3,797,688

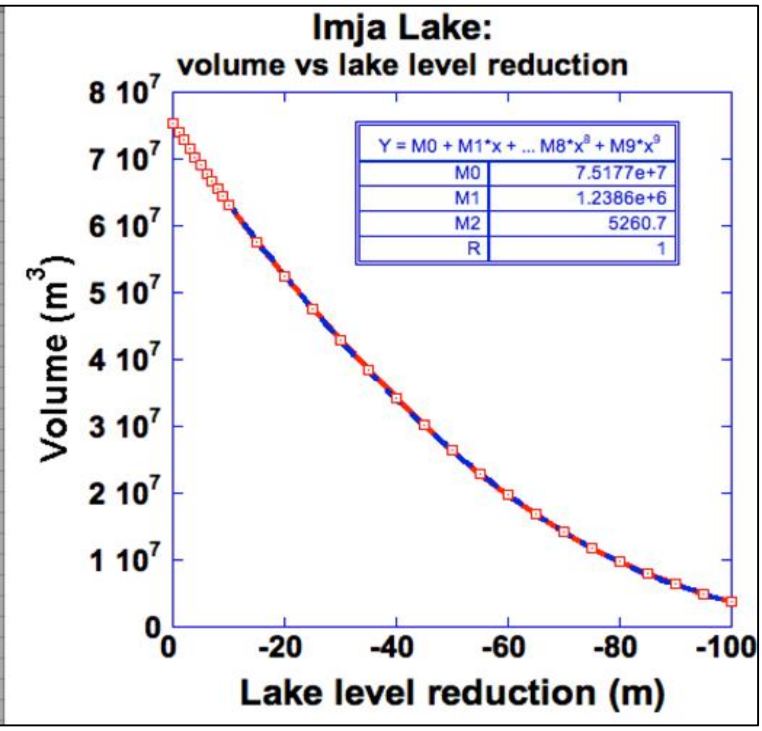


Figure 5.11. Lake bathymetry analysis of effect of lake lowering

5.5. Implications of bathymetry and geomorphology on amount of recent ice loss from Imja Glacier

Ice loss is an ongoing process as Imja Lake grows and the glacier thins and retreats. The amount of ice loss in the last century is stunning, as Figure 5-12 indicates. The schematic reconstruction makes use of the measured bathymetry and elevations of old lateral moraines, plus educated guesses about the surface profile of the glacier in former times. The moraine heights plus the lake bathymetry indicates that as recently as a century ago 300 meters thick of ice existed and has disappeared from where now there is the lake. Additional ice may still exist on the lake bottom. The older, higher, more vegetated moraine—presumably from the Little Ice Age—indicates even thicker ice somehwat earlier, guessed to be 18^{th} century.

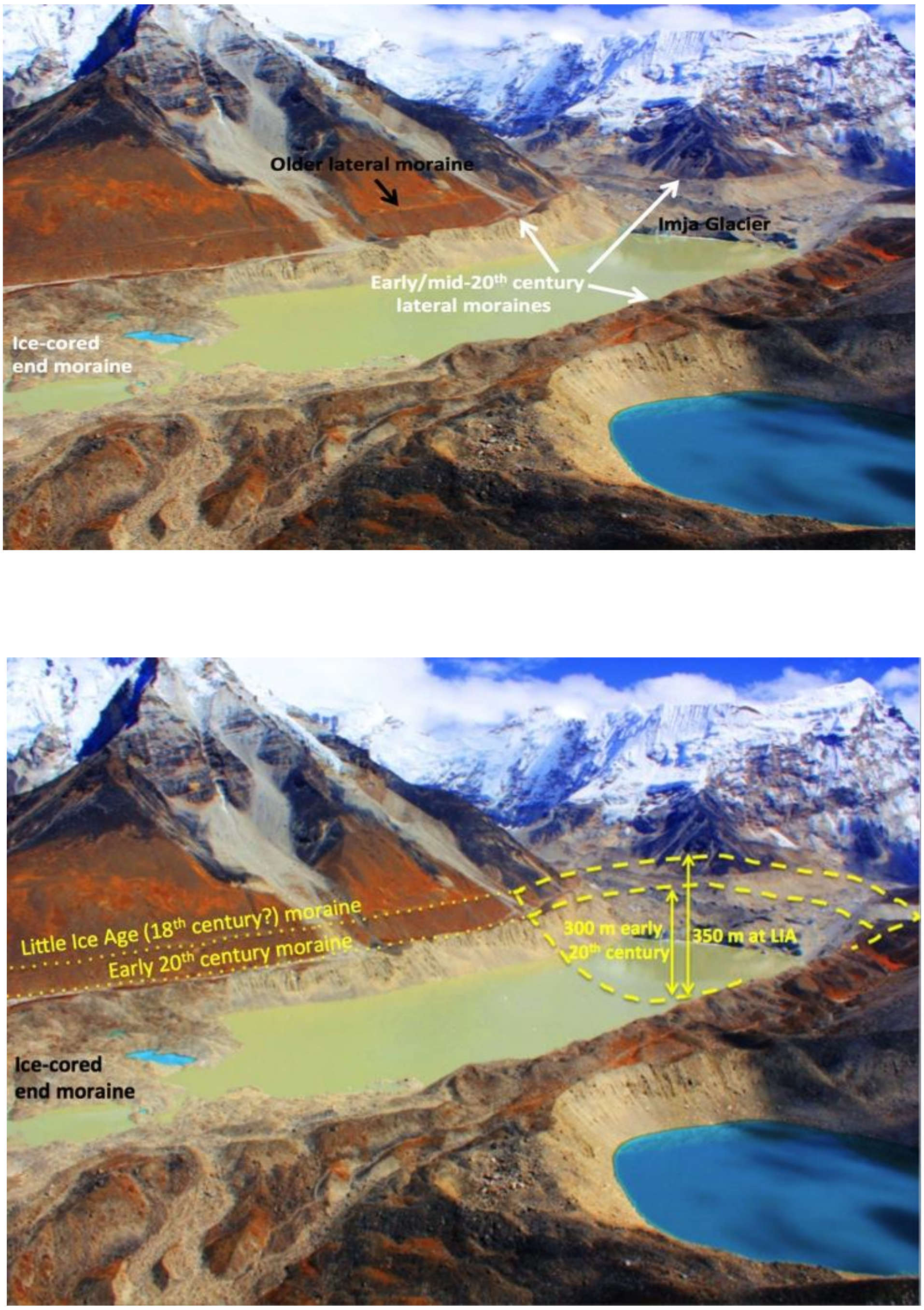


Figure 5.10. 2010 photo stretched (exaggerated) in color and contrast to bring out subtle details of the lateral moraines (top panel). Bottom panel: schematic with reconstructed ice thicknesses corresponding to the two moraines. (Photo by J Kargel), Oct 2010).

Chapter Six

6 HYDROLOGICAL ANALYSIS AND MODELING OF IMJA LAKE

6.1. Hydrologic analysis: low flow and high flow (“normal climate”)

6.1.1. Observations at Dingboche and scaling to Imja Lake

Assessment of annual high (and low) discharges is related to the observed weather records at Dingboche scaled in area to the Imja Basin. Specifically, we assessed a 100-year flood based on the weather records. "Avg Imja Basin” monthly values are the monthly averages measured at Dingboche times 0.28, which is the area of the “Imja” Basin divided by area of “Dingboche Basin” (Fig. 6.1). In the analysis that follows, we make use of this set of calculated values. We did not consider any maore sophisticated scaling relation (for example, to evaluate effects of different microclimates in the two basin areas) to be warranted by available data. From this simple scaling factor and the Dingboche daily records of discharge, it is estimated that the probability is 99.997% for one day per 100 years flood discharge (daily mean) is 5.7 m^3/s (Fig. 6.1), corresponding to the most severe flood likely per century, given the assumed validity of the decadal record of discharge extrapolated to 100 years. Statistics of small numbers (black-

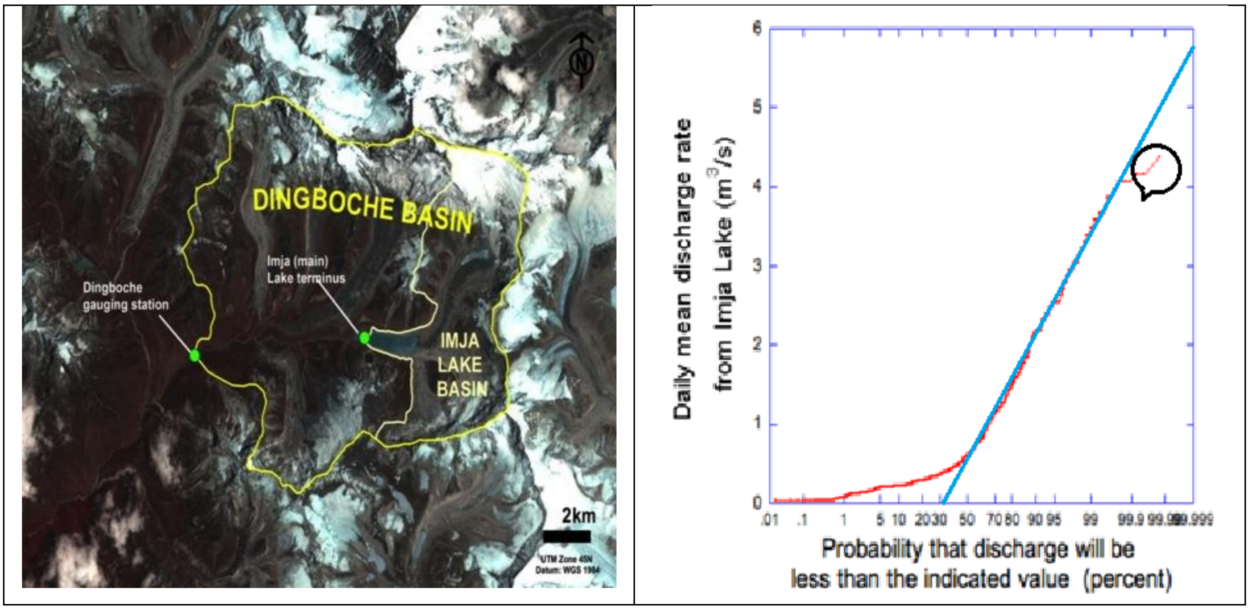


Figure 6.1. Imja Lake and Dingboche basins (left panel) and Imja Lake daily discharge record (right panel). Values are taken from the Dingboche gauging station data (1988-1998 plus 2009), multiplied by 0.28 to account for the smaller size of the area draining into the Imja Lake basin. In the right-hand panel, the blue line extrapolates to a 100-year flood (peak 1-day discharge) of 5.7 m^3/s. The black-circled data represent statistics of small numbers but could extrapolate to a smaller 100-year flood.

circled points in Figure 6.1) should be disregarded for this estimation, so we use a linear extrapolation in the standard graph format of probability versus discharge (Figure 6.1).

A 10-year daily hydrographic record at Dingboche is calculated to annual sums and monthly mean data, and scaled down to monthly mean discharges at Imja Lake (using the 0.28 area scaling factor) in Table 6.1. The ten years are 1990-2000, with 1999 not complete, so it was eliminated.

Table 6.1. 10-year monthly mean hydrographic data measured at Dingboche and monthly means calculated for Imja Lake assuming validity of the 0.28 basin-area scaling factor.

Station number: 666													
Location: Dingboche											**Latitude: 27 53 40**		
River: Imja											**Longitude: 86 56 40**		
				AVERAGE MONTHLY AND YEARLY DISCHARGE (in m^3/s)									
Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
1990	1.42	1.50	1.42	1.44	1.83	1.97	5.70	4.44	2.97	1.88	2.14	1.99	2.39
1991	1.49	1.29	1.56	1.57	2.50	4.21	6.15	6.16	3.95	3.04	3.10	2.12	3.10
1992	1.50	1.42	1.45	1.66	1.95	3.42	4.21	5.19	4.64	3.29	2.63	2.28	2.80
1993	1.43	1.33	1.41	1.49	2.87	3.64	3.78	5.17	3.95	3.04	3.10	2.12	2.78
1994	1.43	1.33	1.07	1.12	1.26	2.61	3.57	4.87	3.95	2.80	2.01	1.43	2.29
1995	1.27	1.26	1.25	1.25	1.90	3.26	4.25	5.25	3.15	2.36	2.40	1.30	2.41
1996	1.30	1.39	1.36	1.46	2.21	2.53	3.59	4.67	4.03	2.69	1.60	1.32	2.35
1997	1.30	1.37	1.45	1.46	2.22	3.12	5.09	5.43	3.93	2.89	2.24	2.00	2.71
1998	1.72	1.77	2.02	2.54	3.18	5.03	3.95	5.00	3.91	3.05	3.11	2.13	3.12
2000	0.98	1.02	1.15	1.63	2.01	2.74	4.56	5.60	2.43	1.65	1.24	0.88	2.16
Average	1.38	1.37	1.41	1.56	2.19	3.25	4.49	5.18	3.69	2.67	2.36	1.76	2.61
MJA LAKE FROM HIGH RAINFALL (1 MONTH MEAN PRECIP. IN 1 DAY) RUNOFF FROM FRACTION f OF THE IMJA BASIN SURFACE AREA													
Avg Imja Basin	0.38763	0.3829	0.39608	0.43727	0.613926	0.91089	1.255937	1.44972	1.033661	0.748064	0.66012	0.49211	

Based on our analysis only of the observed discharge record (not extrapolated to 100 year weather anomalies, but only using the observed record and using the 0.28 area scaling factor) the following conclusions are drawn about the flow statistics of the Imja Lake outlet:

- Annual mean flow at Imja outlet (calculated from the area-scaled Dingboche record) is about 0.7307 m^3/s.
- Maximum measured daily peak discharge is 4.4 m^3/s.
- Minimum daily peak discharge in a year is 2.2 m^3/s (Fig. 6.2).

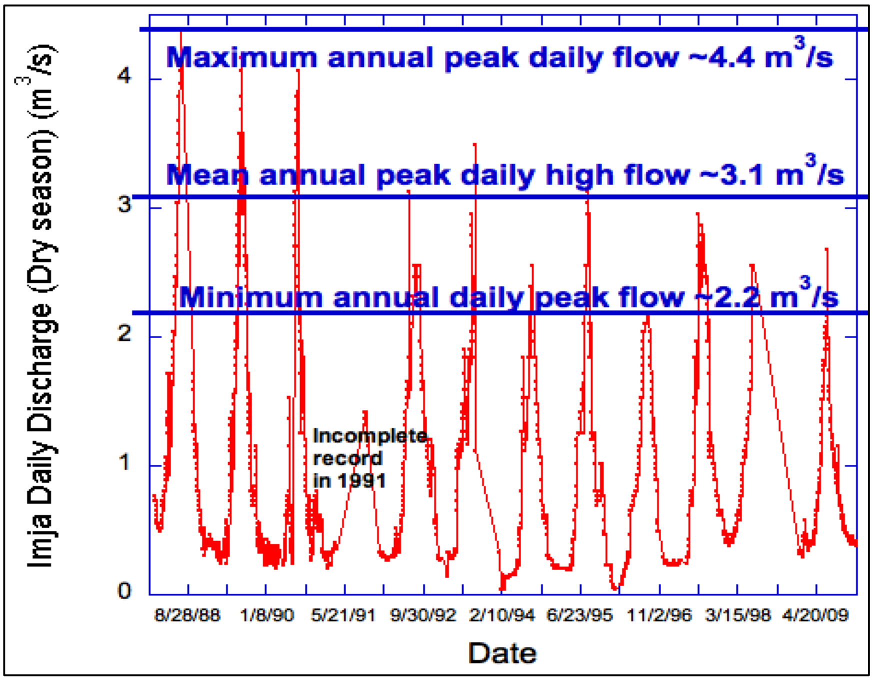


Figure 6.2. Annual flow discharge daily records of Imja Lake to assess maximum discharges (peak spring/summer values). Values are from the Dingboche gauging station multiplied by 0.28 to account for smaller area draining into Imja Lake.

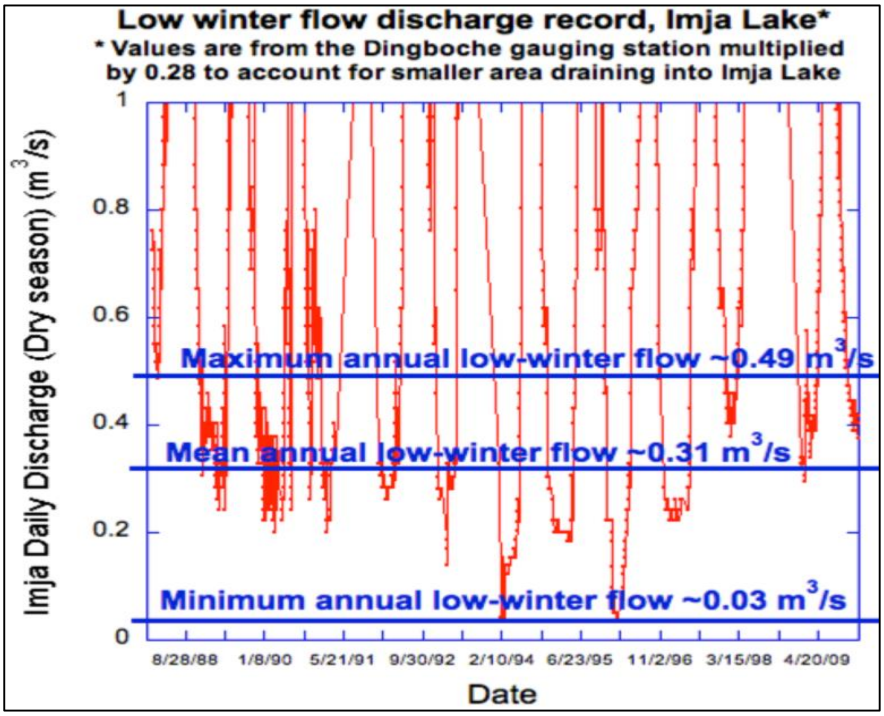


Figure 6.3. .Minimum(low winter) annual flow discharge from daily records of Imja Lake. Values are from the Dingboche gauging station multiplied by 0.28 to account for smaller area draining into Imja Lake.

Similarly, we evaluated the record for low-flow conditions, as requested by UNDP (Fig. 6.3):

- The highest recorded low winter flow value (again using the 0.28 area-scaling factor applied to the Dingboche record) was 0.49 m^3/s.

- The mean winter low-flow value was 0.31 m^3/s.

- The lowest recorded winter low flow was only 0.03 m^3/s.

Finally, we considered the total annual discharge datasets:

- Total annual discharge at the Imja outlet calculated to be 2.306 x 10^7 m^3.

    1. This is an average discharge per unit area of 614 mm/year.
    2. 614 mm/year compares to the annual average observed precipitation at Dingboche of about 380 mm/year.
    3. The difference of the preceding two values (614-380 = 234 mm/year) may be due to either: (a) higher precipitation in the Imja Basin portion of the Dingboche Basin, or more likely (b) contributions from glacier melting equivalent to ~470 mm water equivalent for 50% glacierization. Hence, we infer roughly 50 cm of ice per year glacier thinning and retreat, not counting lake calving retreat (lake calving at Imja Lake simply turns ice to lake-stored water to a first approximation).
    4. This inferred amount of thinning is similar to that reported by direct in situ and DEM differencing based measurements reported by several research groups in the Nepal Himalaya (e.g., Bolch et al. 2012, Racoviteanu et al. 2014). The inferred thinning and retreat is also qualitatively consistent with the rates of glacier thinning that may be visually discerned with the field photographic time series as described in the previous chapter.
    5. The inferred rate of glacier thinning and its apparent influence on Imja Lake discharge (derived from the Dingboche stream gauge time series) suggests that there is a significant component of interannual variation in discharge due to annual weather controls on glacier mass balance.
    6. The annual discharge from Imja Lake is approximately 1/3 of the total volume of Imja Lake. Hence, the mean residence time of water in the lake is of order 3 years.
    7. Extreme precipitation outside bounds of "normal climate"

Lake level fluctuations of Imja Lake due to a normal range of precipitation and runoff during the period of stream gauge records, and those plausibly due to 100-year extremes are pointed as follows.

1. The decadal climate record at Dingboche, area-scaled (factor of 0.28) to Imja Basin.
2. The explicit and implicit assumptions also apply, or their violations are minor.

3. Mean annual flow of Dingboche Basin is 2.61 m^3/s, and the recorded (observed) range of daily values (daily averages) is 0.03 to 4.4 m^3/s during the 10-year record
4. Extreme high flow– this is flow into Imja Lake-- is projected to be about 5.7 m^3/s for a 100-year flood (evaluated as the highest discharge likely for a 1-day period, extrapolated from the available 10-year hydrographic time series at Dngboche, with the 0.28 area scaling factor applied). This would be the 100-year flood for a climatic "business as usual", i.e., similar climate prevailing as that during the 10 years of the Dingboche hydrographic time series; there are no Kedarnath-like floods.
5. Assume that discharge anomalies recorded at Dingboche and scaled to Imja Basin's cause lake level to rise to accommodate increased discharge rate (or lake level lowers for decreased influx) .
6. Use open-channel flow calculator (http://www.eng.auburn.edu/~xzf0001/Handbook/Channels.html), assume trapezoidal channel shape, 2.5 m channel bottom, right side 36 degree slope, left slope 25 degrees, with Manning's roughness coefficient set at 0.07 (appropriate for a bouldery channel), channel gradient 0.0704 (from topographic map delivered by survey team, near outlet of lower pond, = 5 meters per 71 meters gradient in gentler parts of the moraine).
7. Open-channel flow as described for 5.7 m^3/s gives flow depth around 63 cm.
8. The solution depends on fine details of the channel shape, which is not extremely well determined, and Manning's coefficient, and the longitudinal slope (which is only roughly constrained).
9. Add to this a possible instantaneous discharge over a 500 m x 500 m area on the end moraine which may drain directly to the outlet without being buffered by Imja Lake. It is possible to achieve for a few minutes (long enough for runoff from the moraine to reach the outlet) 1 mm per minute, e.g., from a microburst. Microbursts are highly localized (usually ~2-3 km diameter) extreme downdrafts from cumulonimbus cells, often accompanied by a brief episode of intense precipitation (rain or hail). Rapid runoff from a moraine is possible if the soil is frozen at a shallow depth if the day is warm. A typical microburst may issue 20 mm of rain in a 20-minute period. If the affected area is initially thawed, dry and porous, that amount of precipitation can be absorbed, but if it is initially saturated in the permafrost active layer, for example due to a several days of high precipitation, runoff from a microburst over an area 500 x 500 m can attain 4 m^3/s. If such a microburst took place as a part of a 100-year flood, this component of prompt, transient runoff due to the microburst could add to the general 100-year flood's discharge (daily mean 5.7 m^3/s), bringing the total instantaneous discharge to 9.7 m^3/s. This is a summation of two extremes (the 100-year flood plus a brief microburst). Given the recent occurrence several meteorological disasters in the Himalaya/Karakoram region, it seems plausible. Note the recent occurrence of thunderstorms over and near Imja Lake, including during our October 2014 field work.

10. The variety of extreme circumstances suggests that the scenario in point 9 may be a 100-year flood event under "normal" climatic conditions, barring climate change or special meteorological mechanisms that may trigger more extreme situations.
11. Important explicit assumptions, implicit assumptions, caveats, and consequences of errors in assumptions. We consider some of the major assumptions below as we evaluate some scenarios and processes. We do not think that the limitations and assumptions are apt to strongly affect our estimations in any way that would compromise the engineering design, except as mentioned in some potentially extreme circumstances.

6.1.2. ASSUMPTION AND JUSTIFICATION: AREA SCALING APPLIES:

1. Explicit assumption: The partial stream-gauge record at Dingboche can be reliably downscaled to the smaller area of the "Imja Basin" (37.6 km^2) relative to the "Dingboche Basin) (134.0 km^2). The scaling factor is thus 0.28. We calculate Imja Lake's discharge to be: annual mean discharge 0.731 m^3/s, minimum monthly mean discharge averaged over the 10-year Dingboche record = 0.383 m^3/s (February), maximum 1.45 m^3/s (August). The 10-year Dingboche record gives, scaled to Imja Basin's size, the driest recorded month = 0.25 m^3/s (December 1998) and the wettest single month = 1.72 m^3 (Aug 1991).
2. Implicit assumption: The average precipitation and glacier and snowpack runoff rates and annual hydrograph in the Imja Basin are very similar to those in the Dingboche Basin; hence, local orographic slope, elevation, and slope aspect effects are similar.
3. The scaling factor is supported by a limited duration of discharge data acquired during our field work. From 17-22 Oct 2014, we measured Imja Lake's discharge averaging 0.685 m^3/s, which compares closely to the 0.748 m^3/s calculated from the October mean value of the 10-year Dingboche record downscaled to the smaller size of Imja Basin.
4. Likelihood of error: High likelihood of small errors, probably not more than 20% (an educated guess) in annual average and daily precipitation and runoff.
5. Consequences of error: Not very substantial and easily dealt within the recommendation margins.

6.1.3. EXTREME RAINFALL IS NOT THE BIGGEST PROBLEM:

1. Explicit assumption: The spatial scale-temporal scale rainfall event runoff magnitude/frequency scaling that is commonly found in rain-dominated basins does not apply at all in the Imja Basin for daily and shorter periods because most precipitation occurs as snow, which has a longer timescale for runoff.

2. Implicit assumption: Meteorological conditions that may give rise to the once-per-few-decades high discharge events will not be linked to conditions that may also cause widespread rain rather than snow.
3. Implicit assumption: Climate change will not have a large impact on the assumptions above. Likelihood for error: For periods over which we have records, i.e., decadal periods, the assumptions above will likely hold true, because climate change is not having a huge impact on decadal and shorter periods, and in recent experience, rainfall only occurs at the lowest elevation within the Imja Basin. But for multi-decadal periods, both the implicit and explicit assumptions are probably wrong; that is, there will likely be high-intensity rainfall events across much of the Imja basin up to 5500 or even 6000 m (i.e., most of the basin's area). Note that such extreme rain events have already occurred in other parts of the Himalaya-Karakoram up to about 5000 m, e.g., Kedarnath monsoon rain disaster of 2013. Recall also the Tropical Cyclone HudHud extreme snow event in October 2014, which involved heavy rain at elevations approaching Imja Lake. Within a few decades, such events will hit areas several hundred meters higher than they presently can. It might be a gradual shift where such events are increasingly probable, but we do not rule out possibilities that sudden climatic shifts may cause such events to occur earlier than expected.
4. Evaluation of extreme discharge conditions and risk factors that may affect the integrity of Imja Lake's damming moraines and of any engineering structures

There are two risk factors that may affect the integrity of Imja Lake's damming moraines and of any engineering structures, and each of these has several sub-types, and most of the mainly non-meteorological mechanisms can nonetheless have extreme weather as a component of a trigger mechanism. Thus, extreme weather—and by extension, changing climate—plays into many GLOF-generating scenarios.

1. Meteorological cause outside the bounds of "normal weather":
   -- Extreme rainfall events
   -- Extreme snowmelt and icemelt events (extreme hot and sunny weather)
   -- Exceptionally large debris flows triggered by extreme rainfall or melting events.
2. Non-meteorological causes (though there can be weather or climate change links):

   -- GLOFs and overfilling of Imja Lake from supraglacial ponds

   -- Sturzstrom events and overfilling

   -- Cirque headwall collapses: overfill, tsunamis, drainage blockage

   -- Glacier calving due to disarticulation and flotation-related break-up.

   -- Lake bottom ice flotation

-- Sudden melt-through and piping through the end moraine.

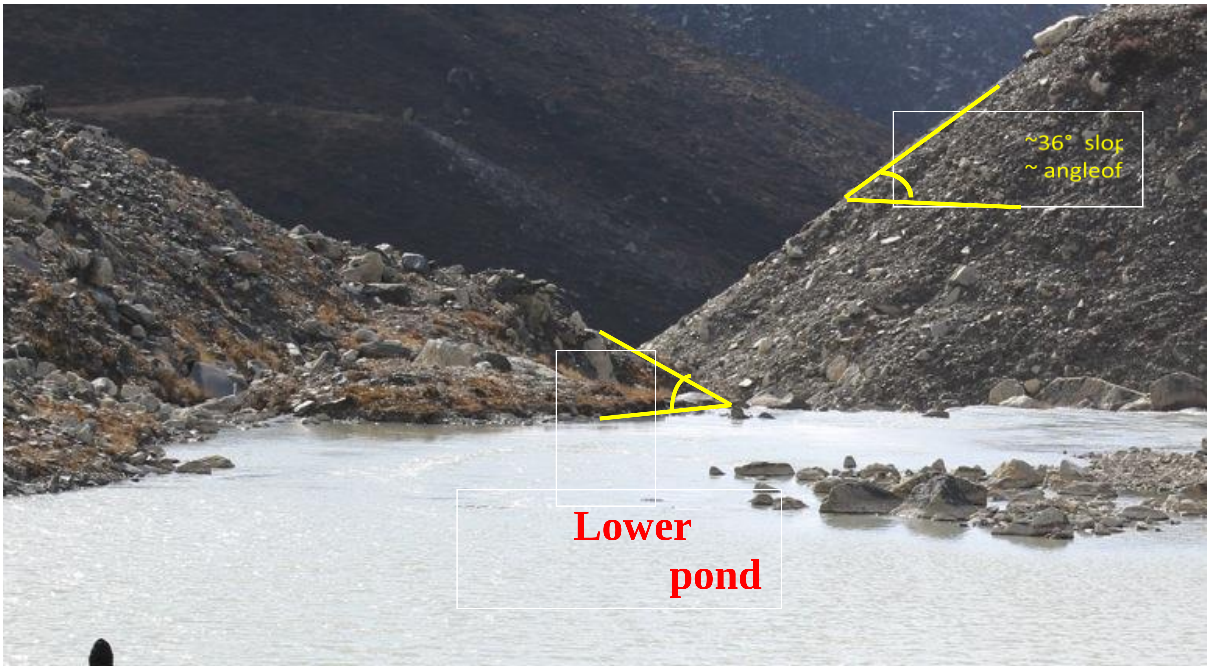


Figure 6.4. Outlet from Imja Lake viewed downstream from lower pond on the damming end moraine shows very steep slopes of an unstable moraine (October 2010)

Under the present climate it does rain sometimes at Imja Lake, although by far the major form of precipitation is snow. Under the present climate, snow cover is commonly absent over 50% or more of the basin's area during the late spring, summer, and early to mid autumn, especially those areas lower than 5500 m (Fig. 6.4). Many of the surfaces that are lower than 5500 m have low water infiltration potential, e.g., bare glacier ice surfaces, mountain bedrock, areas with very thin soil layers or a very thin active layer beneath which is ice-saturated soil (hence is impermeable). Rainfall may have a time constant of typically 2 hours to run off into Imja Lake from most points within the 5500 m elevation bounds where heavy rainfall potentially may occur. In any case, it is much less than 1 day. Extreme rainfall models should be considered using a factor *f* of the basin's area from which rainfall drains rapidly into Imja Lake.

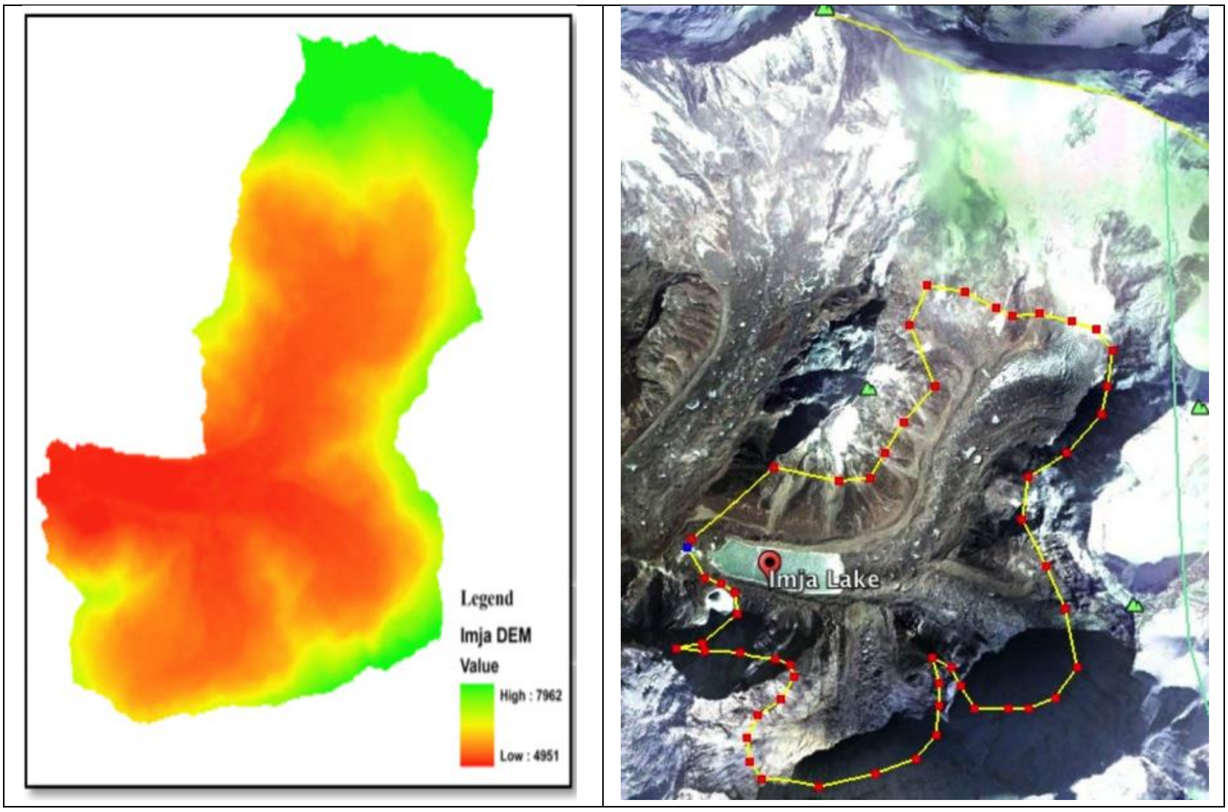


Figure 6.5. Distribution of elevation in Imja Lake basin (Left hand side) and Imja Lake basin below 5500 m (Right hand side)

6.1.4. Lake level rise due to an extreme rainfall event

Monthly resolved mean discharge data for the Dingboche Basin is used to estimate the discharge for Imja Basin (scaled by factor 0.28 to account for the areas of the basins), and "1-day flood" is computed, where the mean monthly total precipitation falls in just 1 day and runs off from a fraction *f* of the Imja Basin's area, immediately going into Imja Lake. Lake level rise calculated that could result from the high rainfall runoff into Imja Lake for 1 day anomalous rainfall runoff occurring from a fraction *f* of the Imja Basin's area. Discharge is calculated for an extreme case of a 2-day precipitation event involved 2 normal August's worth of precipitation, and all that precipitation running off into Imja Lake from 60% of the basin's area (*f* = 0.6). Lake level rise and discharge increase must play off with one another in order to accommodate the extreme-flood influx. Such a flood, while extreme, is not implausible. The amount of precipitation involved is similar to what Tropical Cyclone HudHud delivered to the Annapurna region in October 2014. If that storm had hit with 5° C warmer temperatures (perhaps August instead of October) and hit Imja instead of Annapurna, rain would have fallen instead of snow to 5300 m or higher. Such a flood scenario could have taken place. The chances of this happening are increasing as climate warms. A big worry is that a 'Kedarnath'-like scenario could saturate moraine soils, which then might be subject to rapid debris flows and rapid erosional degradation, channel enlargement, and maybe a GLOF. A stabilized channel even without much lake lowering would help.

Either lake level must be permitted to rise by the calculated amounts, or discharge rate must be permitted to balance the anomalous influx, or both. In nature, both happen, and in an engineered system, both also will happen. We calculate an extreme case of a 2-day flood amounting to 2 Augusts' worth of normal precipitation falling in a 2-day period, and runoff occurring promptly from across 60% of the Imja Basin. This is almost a Kedarnath type situation (or HudHud with rain instead of snow) but should be considered to design a relatively secure GLOF mitigation system. Under this extreme scenario, anomalous influx to the lake attains 26.09 m^3/s, and total 2-day flood volume is 2 days X 2.25 million m^3/day. This is in addition to the background flow, which for August is 1.44 m^3/s, totaling 27.54 m^3/s influx. The anomalous influx cumulatively amounts to 4.5 million m^3 over 2 days. Lake level rise could be 2 X 1.76 m = 3.42 m in the limiting case that discharge does not also increase. Since both flood-stage discharge and lake level will rise until the anomalous influx is dealt with by anomalous cumulative discharge, the actual lake level rise and required discharge will be less than these amounts (Fig 6.5).

Discharge is calculated using open-channel flow calculator (http://www.eng.auburn.edu/~xzf0001/Handbook/Channels.html), assumes trapezoidal channel shape, 2.5 m channel bottom, right side 36 degree slope, left slope 25 degrees with Manning's roughness coefficient set at 0.07 (appropriate for a bouldery channel), channel gradient 0.0704 (from topographic map, near outlet of lower pond). Red circles are measured values from the field team, made in October 2014.

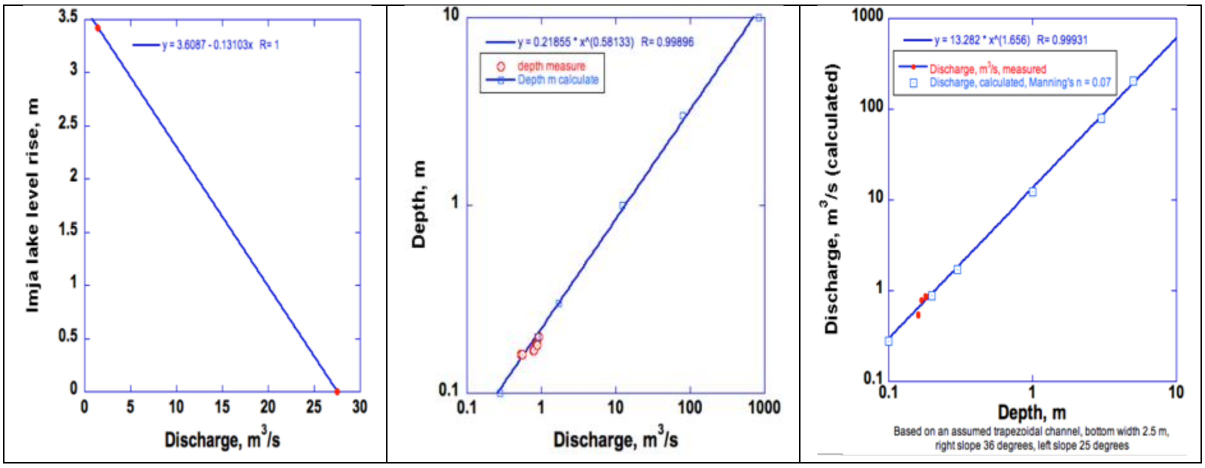


Figure 6.6. Playoff of Lake level rise versus flood discharge rate for the flood scenario (Left hand side) and depth-discharge relation (right hand side).

6.1.5. Simultaneous solution of lake level rise and discharge level for flood scenario

Let x = discharge rate (not necessarily—usually not– the same as the influx rate)

y = lake level rise above "normal" level

z = water depth in outlet channel

2 equations:

$$y = 3.6087 - 0.13103x \qquad (1)$$

$$z = 0.21855x^{0.58133} \qquad (2)$$

Let y = z (appropriate for flow much greater than “normal”)

$$\text{Thus} = 3.6087 - 0.13103x = 0.21855x^{0.58133} \qquad (3)$$

Simplify:

$$x^{0.58133} + 0.59954x = 16.512 \qquad (4)$$

Solve equation 4 by iteration to give the simultaneous solution:

x = 18.46 m^3/s discharge

Now solving equation (1), we find y = 1.19 m lake level rise

6.2. Non-meteorological factors causing exceeding high discharge and possible GLOF triggers

6.2.1. Possible GLOF triggers

Possible critical hydrological conditions that could trigger a GLOF or destroy the GLOF mitigation engineering structures are the important part of design of structures. It should be clear that ordinary high runoff due to a normal wet week of weather, or higher than average spring snowmelt is not the flow condition that would be of greatest challenge to mitigate. It is not even the 100-year flood. It is anomalous glaciological events that may occur rarely but spectacularly, that are of greatest concern and challenge:

- GLOFs into Imja Lake and overfilling of Imja Lake from supraglacial ponds
- Sturzstrom events and overfilling
- Cirque headwall or moraine collapses: overfill, tsunamis, drainage blockage
- Glacier calving and submerged lake bottom ice flotation
- Sudden melt-through and piping through the end moraine.

For the case of a small and slow GLOF (8 million m^3 in 12 hours), a natural or engineered solution lies on the two lines. The simultaneous solution is found in the following equations. With further supraglacial lake development– which we reiterate can take place within just one to two decades from now– much larger GLOFs are possible and they may be much more rapid than modeled

here. The end moraine can easily become overwhelmed, and this would likely trigger a large GLOF from Imja Lake.

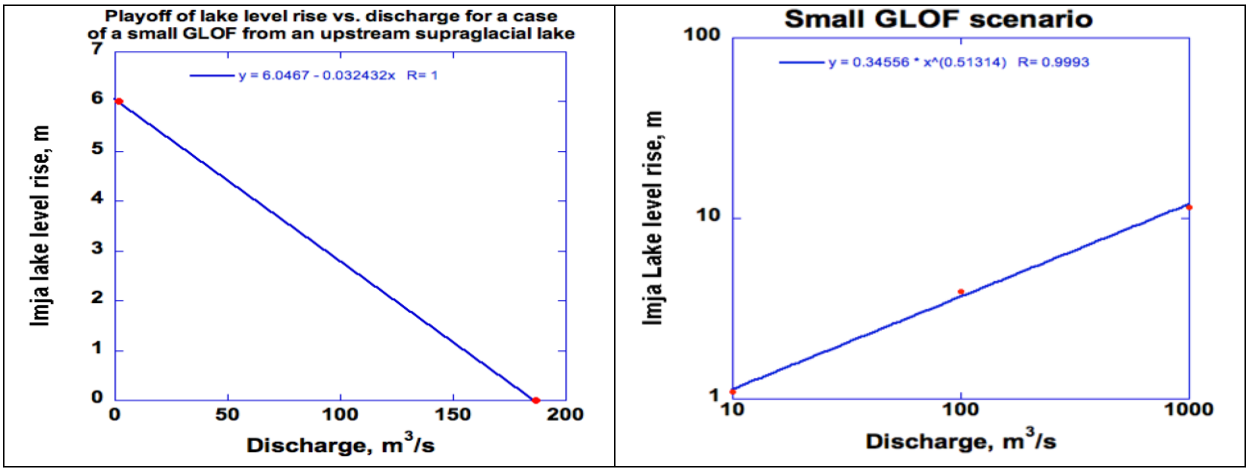


Fig. 6.7. Playoff of lake level versus discharge for a case of small GLOF from and upstream supraglacial lake

6.2.2. Rockfall and landslide damming

Rockfalls and landslides– lower energy per unit mass than sturtztroms are common and can be of very large magnitude in the Himalaya/Karakoram region. Stream blockages by rockfalls and landslides are very common in the HKH. Rockfalls may occur by moraine collapse or by bedrock failures on steep, high slopes. Lake Gojal in Pakistan grew to more than 100 m deep and 22 km long in the 5 months after a rockfall dammed the Hunza River (Pakistan). Rockfalls or landslides could occur into Imja Lake or up valley from it. The outlet of Imja Lake could be directly blocked, so that the lake level quickly rises and potentially bursts out of its new confines, or a stream up the valley might form even supraglacially and then burst into Imja Lake, which may then overfill. Outburst from such a lake is likely (if such an impoundment lake forms), though whether it drains slowly and uneventfully or rapidly and catastrophically depends on the shape and size of rockfall and other individual circumstances. This type of damming and sudden release of impounded water is a present and major risk. However, engineering mitigation seems rather impossible.

6.2.3. Calving

Calving is commonly considered a possible cause of GLOFs, and it may be important sometimes. However, the energy released in most calving events is not large, and if the ice falls into shallow water over an apron of debris and ice, as it commonly does, the energy is quickly dissipated. Likewise, if calving is a fast-paced “crumbling” process, or the ice slowly “rolls” into the lake, the energy is delivered over a long enough period that the waves are not very substantial. However, sometimes deep-water calving occurs in places where water undercuts the glacier by melting. If we consider a piece of ice 200m (cross-valley) x 30 m (down-valley) x 50 m (high) (volume 300,000 m^3) and a drop of 45 m, giving a release of gravitational potential energy = 1.2 x 10^{10}J. If dumped in one piece, it can generate a significant wave. Consider the wave power formula for

wave power per unit length (l) of the wave = wave energy (E_w) per unit-length (l) and per wave period (t) = (E_w/tl)= rg^2H^2t, where r is water density, g is surface gravitational acceleration, H is the main wave height. Recast to solve for H, we have H = square root of ($64pE_w$)/(t^2lrg^2) = 35 m for an assumed 10 second wave period and assuming one wave carries almost all the energy. The wave might generate a large tsunami as it shoals at the other end of the lake. The great depth of Imja Lake at its eastern end approaching the calving front is a point favoring deep-water calving and hence applicability of the deep-water wave power formula. The large size of icebergs also attests to this process. They won't all generate big waves, but some might. It will be a very rare and large calving event with just the right geometry that generates a large wave that is still large by the time it reaches the end moraine. But considering how many calving events occur, it may be a factor that should be considered, though it probably cannot be easily engineered to mitigate. The highly crevassed structure of Imja Glacier does not favor such large calving events as calculated, but even so, smaller waves of 15 m or higher amplitude are probably generated from time to time. Those, too, are probably not very common, because if they were we would see more signs of tsunami activity. However, there may be some signs of tsunami spillover across the lateral moraines.

6.2.4. Submerged glacier flotation-induced waves

Somos-Valenzuela et al., (2014) suggested that a large mass of glacier ice is deeply submerged beneath Imja Lake. This would have been, to some extent, inevitable, because Imja Lake started as supraglacial ponds, and it took time for the ponds to melt down to the glacier bed. Whether massive amounts of glacier ice still reside there is still debatable, but the evidence tends to support this idea. The ice is, of course, unstable due to two reasons: melting and buoyancy. It cannot remain there indefinitely. A load of lake-bottom debris (formerly supraglacial debris and slumped moraine and rockfall material) may reduce both instabilities but would not likely preserve the ice for a long period of time. It still wants to melt and float. It may float in small bits at a time, but maybe not. Another GLOF trigger may consist of rapid flotation of submerged ice. Very large piece of ice suddenly floating could induce large deep-water waves, which may have a destructive interaction with moraines or even a tsunami effect upon shoaling at the west end of Imja Lake. This mechanism is probably one of the unlikeliest but also worst-case scenarios. Though unlikely, it should not be disregarded. It must be retained as a "caveat" to any engineering mitigation countermeasure and should be reconsidered and evaluated quantitatively when data permit.

Iceberg volume undergoing flotation: 100 m thick x 300 m wide x 300 m long.

Vertical distance to stable floating position: 100 m higher.

We roughly calculate the energy involved. Buoyant gravitational potential energy of the

submerged ice, E_i, is Ei = $(r_w-r_i)V_igh$, where:

r_w is the density of water

r_i is the density of ice

V is the volume of ice undergoing flotation = 100m x 300m x 300m = 9×10^6 m^3

g is surface gravitational acceleration of the Earth = 9.8 m s^{-2}.

Thus, $E_i = 8.82 \times 10^{11}$ J. The initial waves will be enormous, but after some time a "sea state" will emerge, where smaller waves carry the energy released by the flotation event minus that dissipated by wave-wave, wave-shore, and bottom interactions. As a thought experiment, we consider the instantaneous transition of the flotation energy to a sea state, where the energy density of waves averaged over the sea or lake surface is $E_w = rgH^2/8$, where E_w includes equi-partitoned wave kinetic and potential energy, and H is the significant wave height. With our thought experiment, we know $E_w = E_i$, and solving for H we get 23.7 m as the significant wave height. On one hand, we know that once a sea state is achieved, much dissipation of energy will have occurred already by crashing of waves, so the waves during the sea state will be smaller than this. On the other hand, before a sea state is attained, the maximum waves will be much larger than this because no waves will yet exist on some parts of the lake. Clearly, a potential exists for very large waves and large tsunamis to be generated. We cannot assess the probability of this occurring, as the mechanism has not been observed at Imja or elsewhere.

6.2.5. Other possible types of more dangerous GLOFs

6.2.5.1. Tsunami wave: We have shown some evidence that tsunami waves may have overtopped the end moraine and lateral moraine at several places near the west end of the lake. Wave heights up to 30 m or even 40 m may be implied, which are consistent with calculations based on large mass displacements into the lake or up from the lake bottom. Here we calculate the volume of one big wave based on a simple geometrical model of a half-cylinder: wave half-width (the semi-major axis *a*) 100 m, half amplitude (semiminor axis *b*) 40 m, transverse length of the wave *c* (Imja Lake width) 450 m, volume = p*abc*/2 = 2.8 million m^3. The forward speed of this wave is enough to have most of its volume– we guess 2 million m^3– ride up and crash over the end moraine; additional tsunami waves in a train may come over with smaller volumes. Thus, 2 million m^3 of water, plus ingested alluvial and moraine sediment and ice from the toe of Lhotse Glacier– maybe 3.6 million m^3 in all– may hit the Dingboche area 7 or 8 minutes later in an interval lasting maybe 2 minutes, giving an effective discharge rate of 30,000 m^3/s, giving a flow depth of 19 m. However, it will be moving at possibly 14 m/s, or faster, and thus some of this flood/debris volume may ride 10 m vertical up the slopes adjacent to outside bends of meanders, thus to an elevation 29 m above the channel near Dingboche. This could destroy 2/3 of Dingboche. This is a severe scenario but it is by no means a worst-case scenario. Volumes two or three times this are possible. It is not so much the volume as the compressed timeframe over which this type of GLOF flood elapses. Hence, it should be recognized that there are different

types of GLOF floods that differ in trigger mechanism, volume, and rate of discharge. Some smaller GLOFs in terms of total volume such as this tsunami wave can be worse than GLOFs an order of magnitude larger in total volume.

<u>6.2.5.2. Debris flow:</u> A bigger problem than a flood could be a debris flow, which might easily attain 20 million m^3 or more as it ingests moraines, glacier ice from Lhotse Glacier, alluvial gravels, and other unconsolidated materials. It was this type of GLOF, for instance, that destroyed the Peruvian city of Huaraz in 1941. The down-valley gradient decreases near Dingboche due to prior episodes of debris emplacement. A bouldery alluvial debris fan—probably including prior GLOF-related deposits– extends down to Dingboche, which means that a new deposit laid down on top of the old ones could come to rest on Dingboche. If the debris flow, once laid down, covered an area 400 x 1500 m, it could be 33 m thick on average. It could be thicker or thinner, more widespread or less. The point is, it could cover part of Dingboche. Likewise, Chhukhung is comparably at risk, less so by a GLOF flood than by a GLOF-initiated debris flow.

6.2.5.3. Moraine melt-through via piping

Piping has been implicated in many GLOF triggers, including some in Nepal. End moraine geomorphology indicates the presence of buried ice and thermokarst (collapse features, ice caves or water-filled conduits) development. Decreased elevation shown by prior surveys (Fujita et al.) indicates thawing of ice. Observed seepage demonstrates that water is moving through the end moraine. The possibility exists for piping due to melting of ice by water traversing the moraine interior. This can become a runaway process, because melt enlargement of a tube allows more water to be transferred, hence more heat transfer into the ice-cored moraine and more melting. If large caverns near the water transit route collapse, instant enlargement can occur. Unless cavern collapse also takes place, piping alone may grow the conduit over a period of days; we already showed that this timescale is not a prime concern for devastating GLOFs.

Figure 6.7. Thermokrast collapse structures or surface thaw lakes (pastel blue) in the end moraine (Left hand side) and Thermokrast ice cliff or collapse feature or cave/tunnel structures in the end moraine (Right hand side)

1. GLOF release due to instant conduit enlargement by cavern collapse or crevasse opening
2. The damming end moraine shows evidence of thermokarst development. It is not known how severe this is. Caverns could be water-filled and hydraulically pressurized if there is water-throughput, or they may be air-filled in some parts of the moraine. Some caverns could be filled with refrozen water. Pressure gradients between isolated chambers may be high.
3. Crevasses, at least one of which is water-filled, indicate that there probably is unconfined stress in the end moraine. (Alternatively, these could be relic crevasses, or periglacial ice-wedge cracks.)
4. Measured seepage is not very considerable, so at present hydraulic flow through crevasses, pipes, or caverns is probably not too significant.
5. Sudden breakdown of cavern walls, or more ordinary crevasse opening under high hydraulic pressures or shear stress is possible.
6. A scenario of crevasse opening (10 cm top width, tapering downward to 25 m depth) and conduction of 0.4 m^3/s warm-water flow could slowly widen the crevasse by thermal erosion. Flow may increase until it can start transporting boulders, at which points it may rapidly erode the conduit. Full breach of the moraine may occur with a characteristic GLOF-eroded notch, 100 m wide, 25 m deep, V-shaped conduit, which could convey 23,600 m^3/s of lake water.
7. At Dingboche, the flow would be about 14 m deep and could ride up another 5 m vertical and destroy the lowest structures.

Chapter Seven

7 CONCLUSION AND RECOMMENDATIONS

7.1. Summary/Conclusion

GLOFs are not created equal in terms of their destructive potential. A large fraction, e.g., a quarter, of Imja Lake's volume could drain out in a matter of hours and still not cause extreme damage downstream except to very low-lying infrastructure, such as low bridges and riverside trails, and any unlucky people who happen to be on the lower parts of trails and bridges when the GLOF occurs. Villages could be spared by even very massive GLOFs if they elapse over many hours or a day. We thus define "fast GLOFs" whose proximal hydrographs peak within minutes (even seconds) of initiation of an outburst event, and "slow GLOFs" whose hydrographs peak hours after an event starts and may take a day or longer to complete. A "slow GLOF" may be generated by surface fluvial or debris flow erosional down cutting of outlet channels during extreme precipitation events, especially "Kedarnath" type events, or by piping and partial moraine failure. It is possible that a GLOF might initiate slowly (hours or even days) but then enter a speedier phase as some critical failure takes place. Hence, these "fast" and "slow" GLOFs are not immutable, hard concepts.

A large threat to downstream villages is posed by "fast GLOFs," especially those caused by very large tsunami waves overtopping the moraine. Such tsunamis can be caused by very large and sudden mass movements into the lake (a known and very dangerous process) or by large sublacustrine ice flotation events (a hypothetical process). However they are caused, evidence exists for tsunami waves in glacier lakes– including Imja Lake– that are of a scale that could threaten Chhukhung and Dingboche and potentially other downstream communities. Tsunami waves also could induce rapid full breach of the moraine if points of weakness, such as water-filled crevasses, are ruptured. Chhukhung is partially protected by the topography of the outwash and moraine structure, but a large tsunami wave could overtop these structures in the proximal areas, so Chhukhung is not entirely safe from the worst conceivable events. Dingboche is partially protected by being farther downstream, allowing some degree of flood hydrograph attenuation of peak discharge for tsunami type GLOF emissions, and furthermore the existing channel has a huge water carrying capacity. However, in the worst cases, all but the most elevated parts of Dingboche are highly vulnerable. More distal communities are increasingly protected by distance in regard to peak discharge attenuation in the cases of tsunami wave-type GLOFs, but slow GLOFs have such long discharge periods that the distal villages' downstream distance is not a protective factor. But to remind, by far the most devastating GLOFs would be tsunami-type "fast GLOFs", and their destructive potential is reduced with downstream distance due to attenuation and the brevity of the peak discharge period.

Thermal undercutting by Imja Lake within its end moraine dam (possible, but not known to be happening) and thermokarstic development of the end moraine dam (known to be happening) may allow rapid moraine failure, which potentially could pose a large danger. The GPR and ERT showed very clearly that the end moraine contains ground ice, and furthermore that the ice ifs heterogeneously distributed, with lenses and sills of ice protruding up, and clefts of ice-free areas formed where the streams and ponds occur. This type of structure may be more prone to thermokarstic destabilization of ice-cemented barriers to groundwater flow, as the sills of ice may thin and break down in short periods of time.

Also a danger are large debris flows, which may be triggered by any sort of GLOF or by high discharges associated with “Kedarnath” type events.

Mitigation measures taken against extreme precipitation events, such as 100-year floods or “Kedarnath” type events may be easiest and cheapest to implement but will not effectively counter the tsunami type of “fast” GLOFs that may pose the largest hazard to whole villages.

We offer four sets of assessment summaries–involving progressively more challenging engineering– based on which possible hazard phenomena are to be mitigated under various scenarios. However, following these assessment summaries, we offer our recommendations and the rationale for them.

7.1.1. Scenario 1: 100 year flood

To handle a high-runoff event estimated as a 100-year flood scaled from the Dingboche stream gauge data (based on “business as usual” climate, where the decadal weather record at Dingboche has a quantifiable bearing the century scale). This approach fails to recognize extreme weather events that have lately been occurring in the region. Design for 1 m lake level rise, 5.7 m^3/s daily, and 10 m^3/s instantaneous discharge; thus lower lake by 1.3 m and build engineered drainage channel at least 1.3 m deep, 5 m^2 cross section for gradient 0.07).

7.1.2. Scenario 2, ‘Kedarnath’ type extreme flood

Here we consider extreme precipitation events comparable in magnitude to the Kedarnath monsoon rain event or a rain-equivalent of the HudHud snowfall event. Our model assumes runoff from 60% of the Imja basin area (from below roughly 5500 m elevation), with 2 days of precipitation equivalent to 2 normal Augusts of precipitation. Sooner or later it will happen at Imja Lake under conditions where the precipitation is liquid over a significant fraction of the Imja Basin. Simultaneous solution for the extreme rain scenario gives a lake level rise of 1.2 m and discharge of 18.5 m^3/s. Design margins could be larger, e.g., plan for 2 m lake level rise (thus, lower lake by 2 m), 25 m^3/s discharge; channel at least 2 m deep, 8m^2 cross section for gradient 0.07. Even without much lake lowering, a robustly stabilized drainage channel would help prevent sudden channel enlargement that potentially could be triggered by a ‘Kedarnath.’

Here our analysis pertains strictly to the topic at hand, which is Imja Lake. We do not evaluate here other damages that would be caused much more widely by Kedarnath-type or even rain-equivalents of HudHud type extreme precipitation events. Obviously, such events could be very widely devastating, with high stream discharges, debris flows and ice avalanches blocking rivers, and so on. At that level of disaster, a potential GLOF would be only one among other disasterous events within the bigger event; or the GLOF could be mitigated, without lessening other types of damage.

7.1.3. Scenario 3, GLOF from a supraglacial lake into Imja Lake

To mitigate a small GLOF from a supraglacial lake (from a glacier into Imja Lake) that could develop upstream possibly in the next 10-20 years. This is modeled as a small and slow GLOF into Imja Lake, which produces a more protracted period of higher than normal discharge from Imja Lake. Bigger events may become possible in the same timeframe, although no significant GLOF is possible now. If a signficant supraglacial lake develops, it would take close to 10 years from the present state of the glacier, which has small ponds but not sizeable lakes. In this scenario of supraglacial lake development, a GLOF into Imja Lake could force 100 m^3/s discharge out of Imja Lake and 4 m lake level rise. For now, a sufficently cautious approach can simply make use of satellite monitoring to document the development of today's supraglacial ponds.

7.1.4. Scenario 4: Large mass movements and tsunami

We have no realistic hope of preventing massive destruction potentially to be triggered by the biggest possible tsunamis, but problems due to some significant middle-sized ones (more likely than the biggest possible events) could be minimized with a large freeboard increase (lake level decrease), e.g., 9 m lake level lowering; more would be better. 30 m reduction in lake level would almost eliminate the tsunami risk, though it may be a difficult target to achieve. A 3 m lake level lowering would not significantly reduce the tsunami hazard. We do not have rigorous size-frequency estimates of tsunami-caused floods because this is a challenging fluid dynamical problem beyond scope of this project, and it is also under-constrained by observations. We have a strong sense that the tsunami risk is very substantial. Design request: Reduce lake level as much as possible. Use of conduit pipes or a tunnel to regulate lake level may be somewhat safer than surface conveyance of water through a lake-lowering system, although a more modest engineering approach would be better than no mitigative action. Siphoning, as done at Tsho Rolpa, presents a nother range of options. Nevertheless, a constructed open channel, even if lowering lake level by just 3 or 4 or 5 m (with equivalent increases in freeboard) would be a relatively low-cost way to reduce the chances of a GLOF and reduce the magnitude of one if it occurred.

7.2. Rationale to constrain Recommendations

Considering the wide range of possible flood scenarios, we may reasonably say that it is not feasible to mitigate all possibilities. The easiest challenges to solve would be extreme meteorological events. Engineering to accommodate 18 m3/s, perhaps with some further margins added, would handle almost any conceivable extreme-weather event, including a 100-year flood under a climatic “business as usual,” and a “Kedarnath” like extreme-flood scenario.

A more severe situation could be posed by GLOF drainage of a large supraglacial lake into Imja Lake. This could more easily induce a giant GLOF from Imja Lake than extreme weather. However, such a supraglacial lake does not yet exist upvalley from Imja Lake. The development timeframe is of order 10 years, so this possible future situation can be dealt with for the time being by satellite-based monitoring.

The most extreme type of fast GLOF is our biggest concern, because this is the one set of scenarios that could destroy whole villages. A surface channel cannot deal with a giant tsunami wave. The only hope to mitigate this type of extreme (but not unlikely) threat is to make a large lowering of Imja Lake. 3 m lowering would barely touch the problem and not resolve it. Even 9 m lowering, though helpful, would leave some risk of a huge tsunami-induced GLOF. Only a 30 m lowering would almost eliminate the tsunami threat if much freeboard remained in place. A more practical goal would be lake lowering by somewhere between 9 and 18 m, which would reduce the drainable volume, increase the freeboard and the along-channel width of the end moraine, and decrease the chances that a tsunami wave could overtop the moraine and either emit a large volume of water by itself, or erode the moraine so that a bigger GLOF takes place.

A possibility could exist to use one of the alignments that have been recommended by the geophysical (electrical conductivity and GPR) thematic teams. An alternative to consider would be first to drain Amphulapcha Lake, then bore through the moraine separating Imja and Amphulapcha lakes and achive a major lowering of Imja Lake. However, we rely on the engineering team to make a better suggestion or to develop this one within the cost constraints imposed on the engineering effort.

7.3. Final Recommendations

7.3.1. Recommendations for lake lowering

1. Shallow engineered surface channel capable of conveying at least 18 m^3/s to control erosional effects on the damming end moraine of extreme weather, particularly a “100-year flood,” but also a “Kedarnath-like” (or HudHud rain-equivalent) flood.
2. Lake surface lowering by much more than 3 m, perhaps in the range of 9-18 m if possible, in order to reduce the tsunami hazard.

7.3.2. Recommendations for continued surveying and monitoring

3. We urge monitoring from space and occasional field visits to assess the evolving glaciers, lakes, moraines, and overhanging unconsolidated masses. It is important, for instance, to monitor the possible growth of supraglacial ponds and subsidence of the end moraine.
4. Numerical modeling of different types of GLOFs is needed, including tsunami waves triggered by mass movements down into the lake or by flotation of ice; piping through the end moraine; and downcutting of the end moraine by extreme weather events.
5. The internal structure of the end moraine and lateral moraines and lake flood deposits should be assessed in more detail, to deeper levels, using deep penetrating geophysical tomographic methods. Seismic tomography may help, in addition to improved electrical resistivity and ground penetrating radar surveys during winter and monsoon seasons. The lake floor, submerged part of the end moraine and lateral moraines, ponds on the end moraine, and glacier calving front should be imaged using side-scan sonar. Evidence of cavernous structures, crevasses, or other potential failure points should be assessed. The possible presence and amount of ice on the lake bottom should be assessed, and the possible thermokarstic structure of ice in the end moraine should be determined. Drilling would be another very good approach to assessment of the moraine's internal structure.
6. Hanging masses of ice and unconsolidated debris and mountain bedrock structure should be assessed for potential volumes and likelihood of mass movements.
7. The complete bed topography and ice thickness of the glaciers should be assessed to aid in projections of future dynamics of the system.
8. Chhukhung, Dingboche, and other developments should be carefully surveyed, and GLOF models developed for both slow and fast GLOFs of different causes and different magnitudes (total volume, duration and peak discharge, and sediment/water ratio).
9. The hydrology and climatology/weather of Imja Lake area must be monitored daily and continuously. Hence, an automatic weather station and stream gauging station is needed at Imja Lake. Manually read weather and stream gauging stations could be instituted in Chhukung for redundancy.
10. Thorough reassessment of the physical condition of the glaciers, lakes, moraines, and overhanging masses (hanging glaciers and unconsolidated debris) should be undertaken at least once per 5 years to assure that the system is not changing in unpredicted and dangerous ways. Engineered structures must be inspected at least annually for the same reason. Both satellite assets and experts on the ground are needed.

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