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High Mountain Glacial Watershed Program

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ABSTRACT

Imja glacial lake, located in the Sagarmatha (Everest) National Park of Nepal, is one of the most studied and rapidly growing lakes in the Himalayan range. Compared with previous studies, the results of a sonar bathymetric survey conducted in September of 2012 suggest that its maximum depth has increased from 98 m to 116 m since 2002, and that its estimated volume has grown from 35 million m^3 to 63.8 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, now losing more than 200 m of glacial ice per year compared to estimates of 34 m/yr in 2007. We suggest that the lake has now evolved to a moderately dangerous status primarily on the basis of increased water volume, which has grown to nearly double that contained in the lake 10 years ago.

KEYWORDS: Imja lake, bathymetry, Nepal, glacier lake outburst flood, climate change

1 INTRODUCTION

1.1 Glaciers and climate change, Glacier lakes and GLOFs in Nepal

Newly formed and forming glacier lakes in high mountain regions of the world present a risk of glacial lake outburst floods (GLOFs). (Kattelmann 2003; Richardson and Reynolds 2000). A GLOF is a sudden release of a large amount of lake water into a downstream watercourse, many orders of magnitude higher than the normal flow, and usually triggered by ice avalanches that create surge waves capable of breaching the terminal moraine dam (Carrivick and Rushmer 2006). GLOFs can cause severe damage to downstream communities, infrastructure, agriculture, economic activities, and landscapes because of the sheer magnitude and power of the flood and debris flows produced (Bajracharya et al. 2007).

The rate of formation of glacier lakes in the Nepal Himalaya has been increasing since the early 1960s (Bolch et al. 2012). According to Bajracharya et al. (2007), 24 new glacial lakes have formed, and 34 major lakes have grown substantially, during the past several decades in the Sagarmatha (Mt. Everest) and Makalu-Barun National Parks of Nepal. Accompanying this increase in the number and size of glacier lakes is an associated increase in GLOF events (Ives et al. 2010; Shrestha and Aryal 2011) which now occur on average every 3 to 4 years in the eastern

Himalaya (Yamada and Sharma 1993; Kattelmann 2003). The appearance and danger posed by new glacier lakes in this region has prompted national and regional groups to assess and develop ways to mitigate the increasing GLOF risk to communities, infrastructure, and landscapes downstream of the lakes (e.g., UNDP 2013).

The Khumbu region of Nepal (Figure 1) is regularly mentioned as an area prone to GLOF events. Bajracharya et al. (2007) suggest that at least twelve of the new or growing lakes within the Dudh Kosi watershed of the Sagarmatha and Makalu-Barun National Parks may be "potentially dangerous," based on their rapid growth over the past several decades as evidenced by comparative time lapse, remotely sensed imagery (Bajracharya et al. 2007; Jianchu et al. 2007; Bolch et al. 2008; Watanabe et al. 2009). Byers et al. (2013), on the basis of field-based research combined with remote sensing and flood modeling, concluded that only two of the twelve lakes were, in fact, potentially dangerous (i.e., Chamlang North in Makalu-Barun, and Imja in Sagarmatha). Two GLOFs have occurred in the Khumbu region in recent decades, including one in 1977 from Nare Tsho (Ama Dablam), and one in 1985 from Dig Tsho (Langmoche glacier) resulting in several deaths and major infrastructure losses (Buchroithner et al. 1982; Fushimi et al. 1985; Zimmerman et al. 1986; Ives 1986; Vuichard and Zimmerman 1986, 1987; Hammond 1988; Mool et al. 2001; Ives et al. 2010). Currently, the apparent acceleration of meltwater pond formation on previously stable, debris-covered glaciers such as Khumbu and Ngozumpa, following the precise patterns of Imja lake some 30 years ago, has increased the concerns of local people and scientists alike.

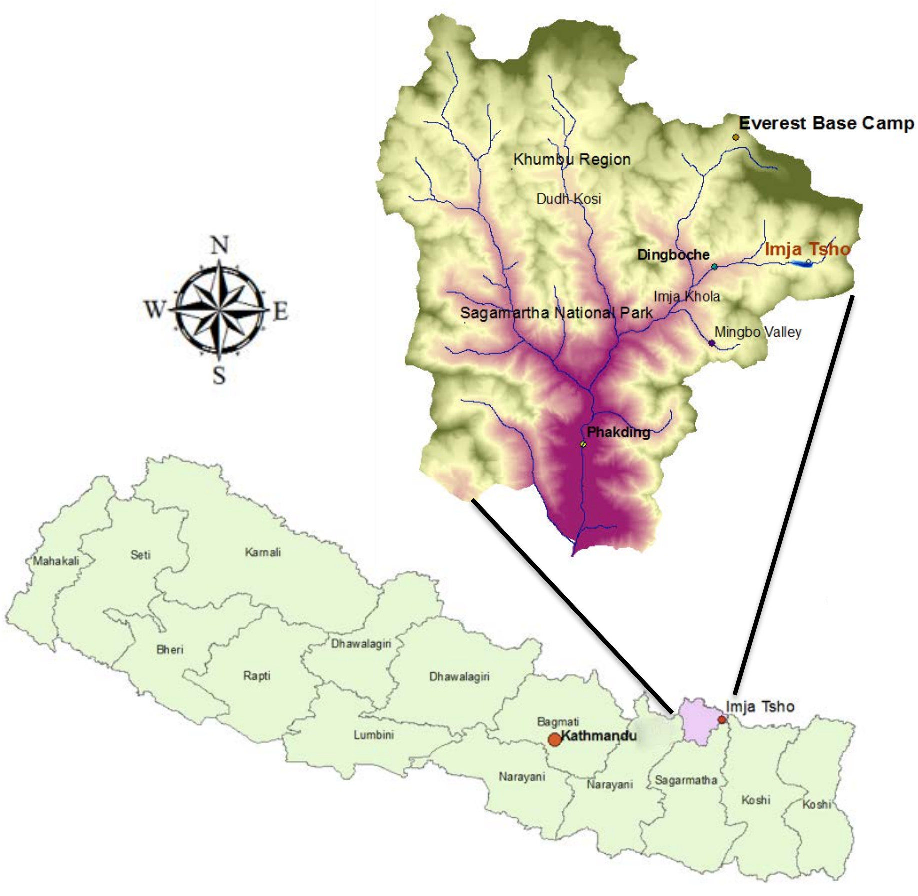

Figure 1. Location of Imja Khola basin within Nepal.

1.2 Imja Glacier and Lake

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. The area of the Imja basin is about 141 km^2, 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 2. Imja lake, September 2012 with Imja glacier to the right, Imja lake in the center, and former glacier tongue and outlet at the front left.

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 the 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). 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, and the presumed melting of this ice 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.

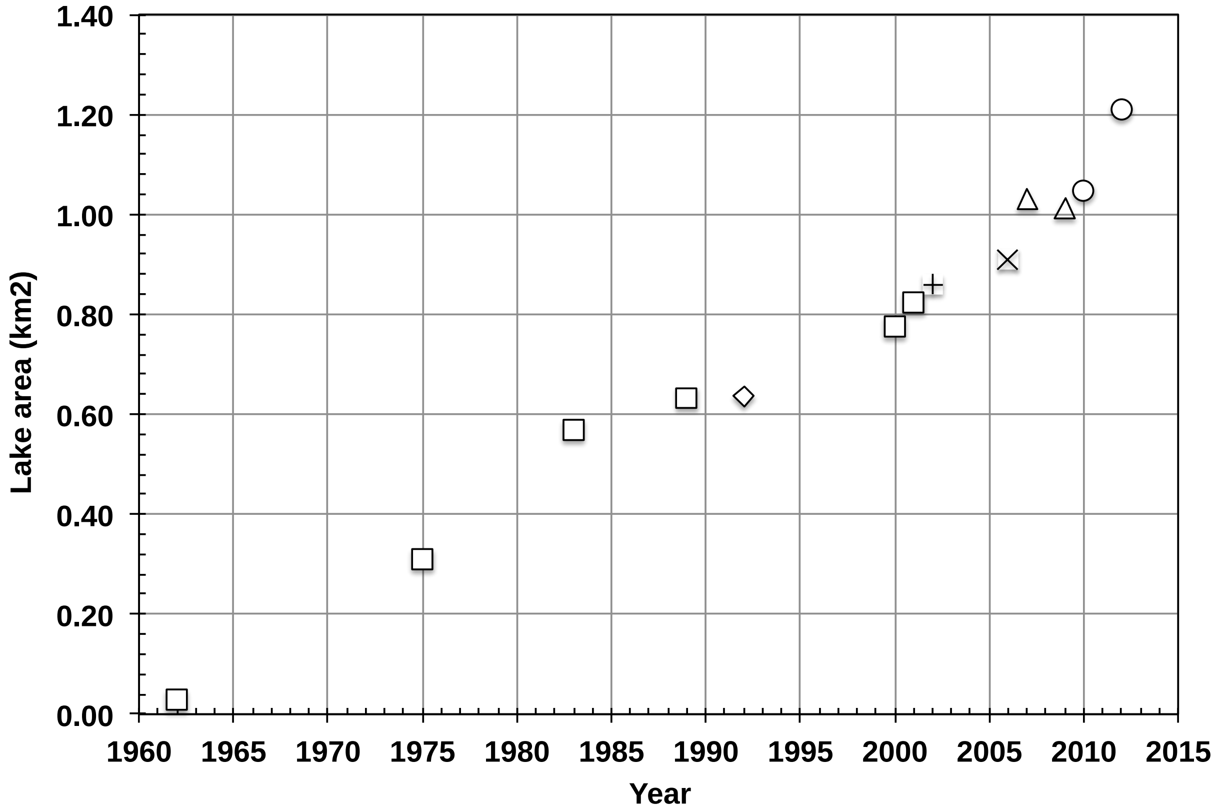

Figure 3. Imja Lake Area Expansion 1962 to 2012 (Source: □ - Bajracharya. et al. (2007), ◇ - Yamada and Sharma (1993), + - Sakai et al. (2003), × - Lamsal et al. (2011), △ - Watanabe et al. (2009), and ○ - This study)

Imja lake is among the most studied glacial lakes in Nepal, if not the world (e.g., Hammond 1988; Watanabe 1994, 1995, 2009; Yamada and Sharma 1993; Yamada 1998; Chikita et al. 2000; Sakai et al. 2003, 2005, 2007; Gspurning et al. 2004; Quincey et al. 2005, 2007; Byers 2007; Bajracharya et al. 2007; Bolch et al. 2008; Hambrey et al. 2008; Fujita et al. 2009; Ives et al. 2010; Lamsal et al. 2011; Benn et al. 2012). For two decades, the lake's unusually rapid growth has led to concerns among a large number of researchers regarding the possibility of a catastrophic GLOF event, while an equally large number maintain that the risk is minimal**.** Yamada and Sharma (1993), for example, mention Imja lake as one of the most dangerous lakes in Nepal, noting that ice is present in the terminal moraine and that the moraines are mostly unconsolidated. Watanabe et al. (1994; 1995) reported rapid melt of the debris-covered ice and significant changes in the outlet that may lead to an outburst of the lake if the outlet complex ice continues melting and the terminal moraine sinks. Bajracharya, et al. (2007) called for urgent mitigation measures to reduce the risk of the lake due to its rapid growth. Imja lake has consistently been ranked in the top three lakes on the Potentially Dangerous Glacial Lakes (PDGLs) list in Nepal, along with Tsho Rolpa and Thulagi Lakes (ICIMOD, 2011).

On the other hand, Budhathoki et al. (2010) suggested that the risk of a GLOF is only moderate. Hambrey et al. (2008) state that the possibility of a GLOF is very low because of the low risk of calving waves, the wide, gradually changing moraine with adequate freeboard, and a free-draining channel. Watanabe et al. (2009) and Fujita et al. (2009) concluded that Imja is relatively stable.

Benn et al. (2012) note that if the outlet channel incision dominates the outlet evolution, the lake may completely drain safely; whereas, if moraine dam narrowing dominates, a GLOF may occur.

The reasons for such a disparity of opinions regarding the level of risk that Imja lake presents is not entirely clear, but may be related to the wide range of sampling techniques employed, short term nature of the average field expedition, challenging working conditions, or exclusive reliance on remote sensing methods alone (Personal comm. T. Watanabe 2012). Nevertheless, the risk has been serious enough to prompt the Government of Nepal to engage in a new glacial lake outburst flood risk reduction project with the United Nations Development Programme in Nepal (UNDP 2013).

Historically, bathymetric surveys of Imja lake were conducted in 1992 and 2002. The 1992 measurements were taken at 61 points around the lake through holes drilled in the ice using a 100 m long fishing line and weight (Yamada and Sharma 1993). The 2002 bathymetric data were taken at 80 uniformly spaced points on the lake using a weighted fishing line (Sakai et al. 2003; Fujita et al. 2009).

In September 2011, May 2012, and September 2012, we visited Imja lake and observed the rapid rate of change of the former glacier terminus. In order to gain a better understanding of the lake's physical characteristics and flood risk potential, we also performed ground penetrating radar (GPR) surveys of most of this area, mapped the ice core of the end moraine (Somos-Valenzuela et al. 2012), and conducted a sonar bathymetric survey of Imja lake and the outlet. Results of the bathymetric survey are presented here.

2 SURVEY

We conducted a bathymetric survey of Imja lake between September 22 and 24, 2012 using a Biosonic EchoSounder MX sonar unit mounted on an inflatable raft. Several transects were measured across the lake, as well as the lake outlet complex of the former glacier tongue of the lake (Figure 3).

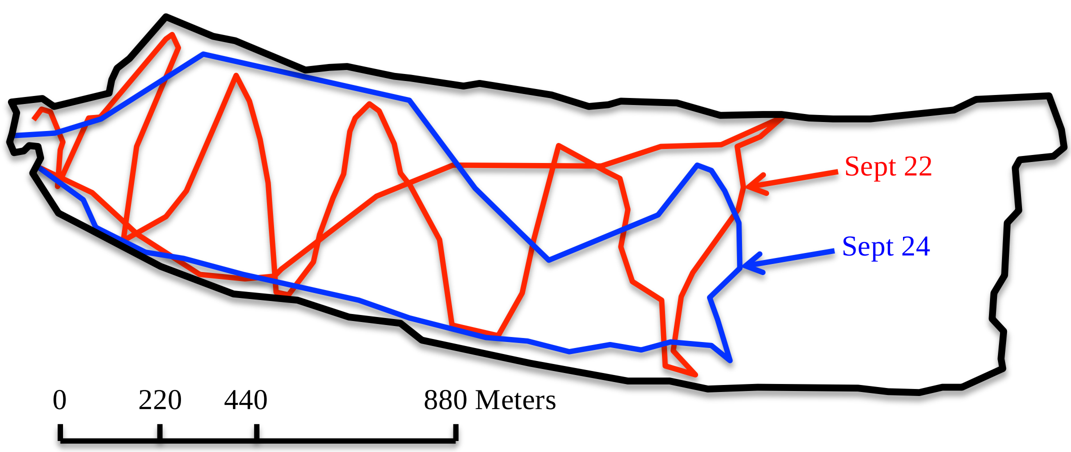

Figure 3. Transects performed during Imja lake bathymetric survey on September 22, 2012 (Red) and September 24, 2012 (Blue).

3 RESULTS

Figure 4 shows a contour map of the depth of the bottom of Imja lake derived from the sonar measurements taken during the two days of surveys. Water depths of 20-60 m were measured near the western edge of the lake (outlet end) and 30-100+ m deep near the eastern (glacier) end of the lake. Because of the thick iceberg coverage on the eastern edge of the lake, transects there were not possible. Elevations deeper than 100 m within the 100 m-contour in Figure 4 were interpolated from the surrounding values; the slope at the up-glacier end (eastern) of the lake has also been approximated. Apparently, the lake bottom has continued to lower as the ice beneath the lake has melted.

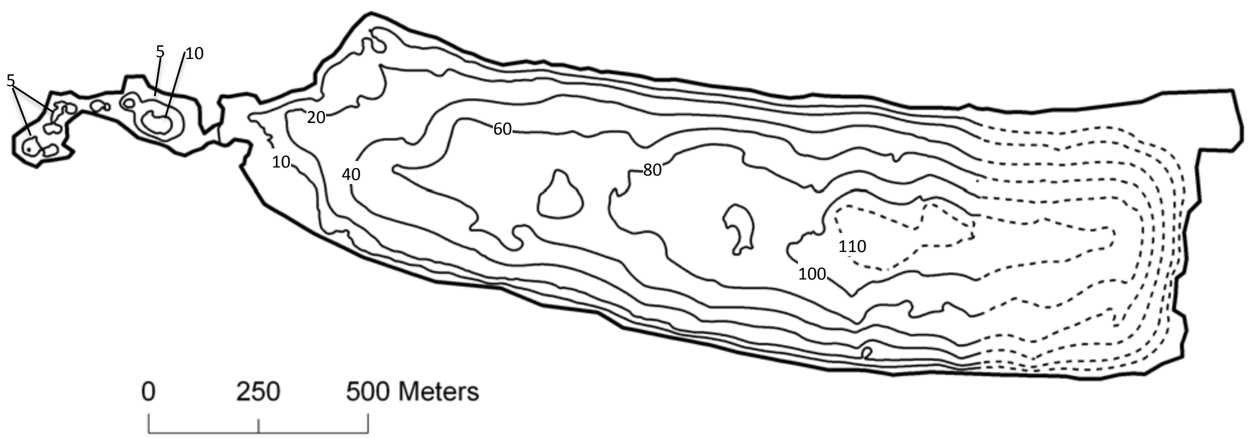

Figure 4. Bathymetric survey results from Imja lake in September 2012. Dashed contours indicate region of interpolated data.

The results of our 2012 bathymetric survey are shown in Table 2, and illustrate considerable variability between those conducted in 2012 and 1992/2002. For example, the previous maximum depth measured in 1992 was 98 m (Yamada and Sharma, 1993), compared with an interpolated depth of 116 m measured by our survey. Additionally, our estimated volume of water in the lake nearly doubles that from the 2002 estimates, i.e., from 35.8 million m^3 in 2002 to 63.8 million m^3 in 2012. The accuracy of the 1992 and 2002 data are unknown, and the comparability of methods used in all three studies is questionable. However, as shown in Figure 5, the consistency of the 2002 and 2012 data from 500 to 1,750 m distance (western part) supports our observations and measurements of a rapid acceleration in growth in the eastern part of the lake.

Table 2. Imja Lake Bathymetric Survey Results

Study	No. of Measurements	Area (km^2)	Volume (10^6 m^3)	Average Depth (m)	Maximum Depth (m)
1992 (Yamada and Sharma; 1993)	61	0.60	28.0	47.0	98.5
2002 (Sakai et al.; 2003)	80	0.86	35.8	41.6	90.5
2012	10,020	1.21	63.8	52.6	116

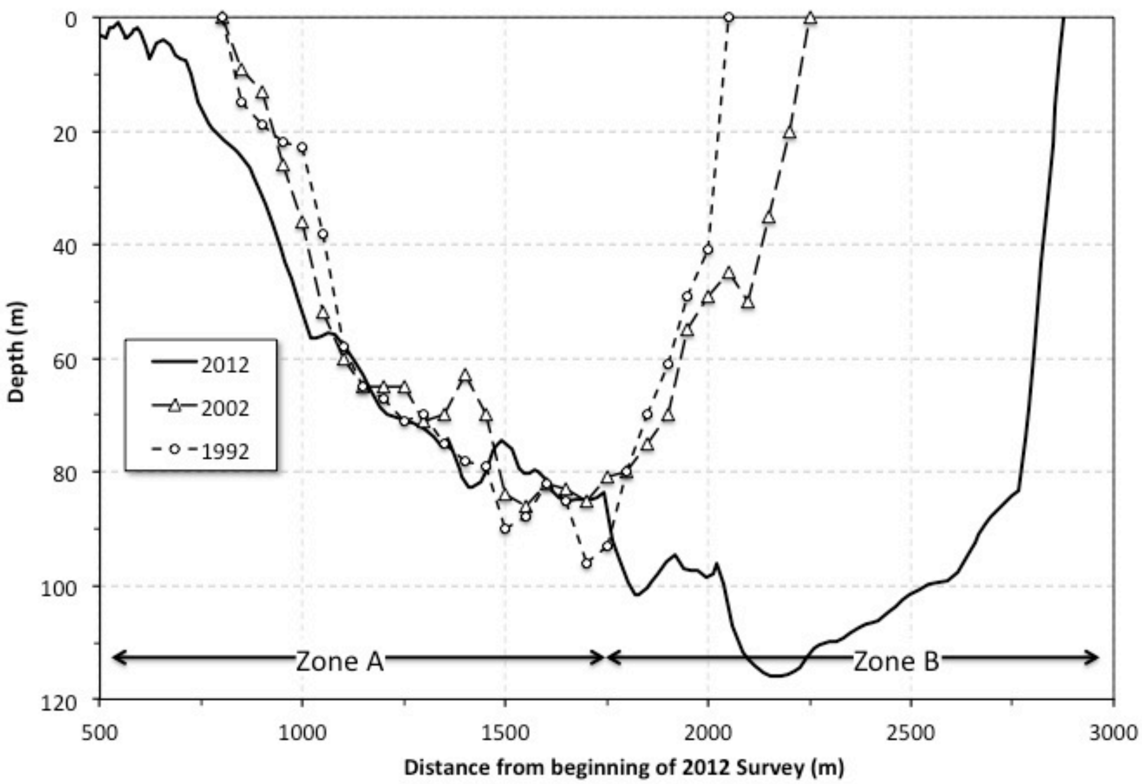

Figure 5. Comparison of 2012 bathymetric survey results with those of the 1992 (Yamada and Sharma 1993) and 2002 (Sakai et al. 2003) surveys.

Table 3 shows that the volume of the lake in 2012 was 78 percent larger than in 2002, increasing at a rate of 2.83 million m^3/yr. Compared to the prior surveys, our results also show that the eastern section of the lake has deepened over the last decade (2002-2012) as the ice beneath has melted, with the average depth increasing by 1.75 m/yr. In the same period, the maximum depth has increased 28 percent, and continues to increase at an annual rate of 5.8 m/yr. Tentative results based on recent satellite images indicate that the area of the lake has expanded 41 percent and is growing at a rate of 0.02 km^2/yr.

Figure 5 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 and the subaqueous melting that has taken place. 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. We estimate that the volume of a GLOF today would be 36 million m^3, an increase from the previous estimate of 21 million m^3 in 2002 (Sakai et al. 2003).

Table 3. Comparison of Imja Lake Characteristics Over Two Decades

Decade	Volume Increase (%)	Volume Expansion Rate (million m^3/yr)	Area Expansion Rate (km^2/yr)	Average Depth Change Rate (m/yr)
1992-2002	30	0.78	0.026	-0.54
2002-2012	78	2.83	0.020	1.75

Figure 5 shows two distinct zones with different depths: zone A, from 500 to 1,750 m (western part), and zone B, from 1,750 m to 2,800 m (eastern part). Reasons for the differences in depth between the two zones are not entirely clear, but may be related to the presence or non-presence of ice at the lake bottom. That is, a lack of dead ice at the bottom of zone A would arrest all further deepening, while the presence of ice at the bottom of zone B would account for its continued deepening. Figure 5 also supports the theory of subaqueous calving in zone B that we have observed repeatedly at the lake. Figure 6 shows results of the bathymetric data for the lake bottom along a longitudinal cross section and the Imja glacier and lake as determined by Ground Penetrating Radar (Somos-Valenzuela et al. 2012). It illustrates the difficulty in defining the boundary between the area underlain by ice as opposed to ice and rock or just rock in Fig. 6. The horizontal line in Fig. 6 shows that at lease half the lake volume will not discharge in the event of a GLOF. Additional lake bottom melting in zone B will deepen the lake and add to the “safe” pool of water.

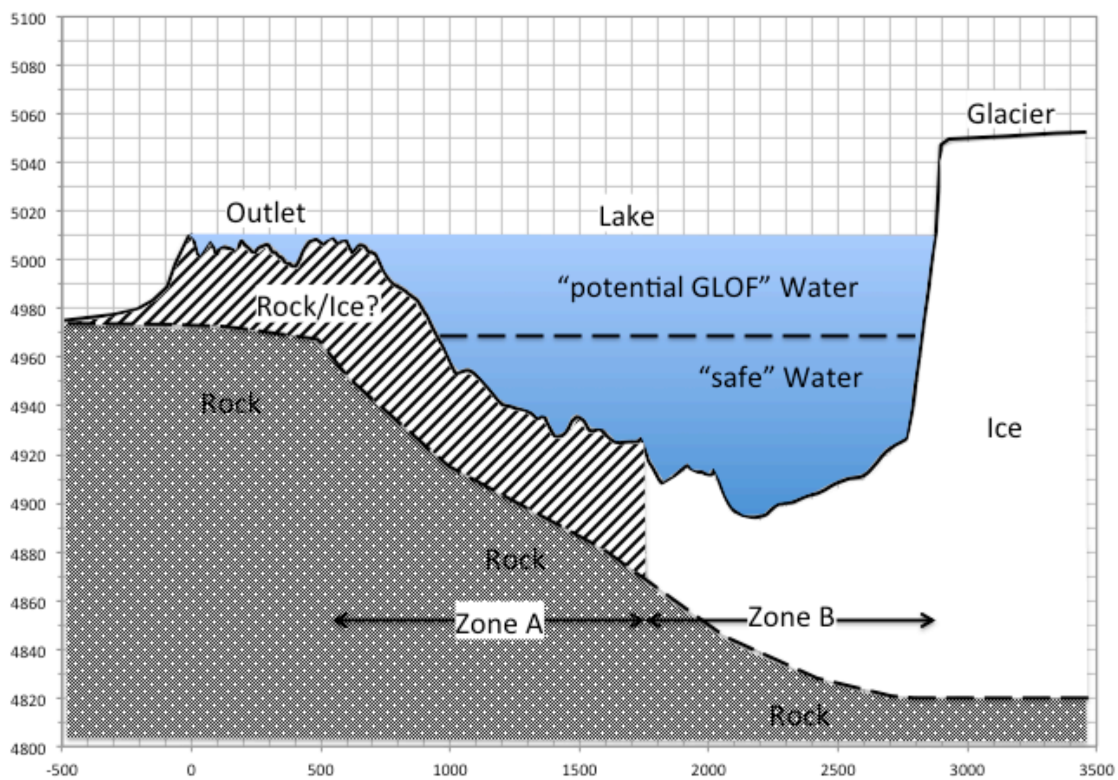

Figure 6. Conceptual model of Imja lake created from recent bathymetric survey and ground penetrating radar survey data.

4. CONCLUSIONS

Imja lake is one of the most studied and rapidly growing glacial lakes in Nepal. Some investigators consider it to be relatively safe because of its slow evolution, while others consider it to be of moderate risk because of the potential for narrowing of the outlet dam due to ice core melting.

Based on our recent measurements of the ice core and observations of seepage at the dam, we consider the lake to be of moderate risk of a glacial lake outburst flood. Compared with previous studies, the results of our 2012 bathymetric survey suggest that the lake has deepened, from 98 m in 2002 to 116 m in 2012. Likewise, the volume has increased from 35.8 million m^3 to 63.8 million m^3 over the past decade as well, a 78 percent increase. The lake volume is increasing at a rate of 2.83 million m^3/yr, and the average depth is increasing by 1.8 m/yr. Our survey results also suggest that the lake bottom has continued to lower as the ice beneath it has melted. Most of the expansion of the lake in recent years has been due to the retreat of the glacier terminus (eastern end of the lake) through calving processes, apparently accelerating based on both time-lapse photography (Byers 2007; 2011) and our own observations. The rapid expansion of the lake in the decade 2002 to 2012, compared to 1992 to 2002, may be due, in part, to acceleration of the calving of the terminus ice-cliff and subaqueous calving as the ice beneath the lake has melted. This is of concern, since the volume of additional water that could be released in the event of a GLOF is now estimated to be 36.3 million m^3, rather than 21 million m^3 estimated 10 years ago. Imja lake continues to be a safety concern for communities downstream of the lake and proposals for reducing the risk of the lake are being developed for possible implementation.

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