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ABSTRACT

A model was developed to assess the impact of a potential glacial lake outburst flood (GLOF) from Imja Lake in Nepal and its impact on downstream communities. Implications of proposed GLOF risk reduction alternatives, including one suggested by local community members, were assessed. Results provided three alternatives that offer significant risk reduction for the communities, including (1) no lowering of the lake and constructing a 60 m flood detention dam, resulting in a 43.2 percent reduction of risk, (2) lowering the lake 10 m with a 40 m dam, resulting in a 57.8 percent reduction of risk, and (3) lowering the lake 20 m with no dam, resulting in a risk reduction of 66.7 percent. An alternative to lower the lake by 3 m with no check-dam, currently under consideration by the Government of Nepal, would result in a 5.2 percent reduction of risk. This alternative does not appear to offer significant risk reduction benefits to downstream communities compared to lowering the lake by 20 m. Results suggest that either the lake must be lowered by significantly more than 3 m (20 m is recommended) or that a downstream flood detention dam be included in the project. One possible method of lowering Imja Lake is to use siphons to drain lake water by 3 m, excavate to the new water level, repeating the process until a total lowering of 20 m is achieved. This method would require the use of 13 pipes of 0.350 m diameter to lower the lake.

1. INTRODUCTION

1.1. Glacier Lakes and GLOFs in Nepal

Recent reports have indicated that glaciers continue to retreat worldwide as a result of contemporary warming trends (WGMS 2013). In the Mt. Everest region of Nepal, 24 new glacial lakes have formed and 34 have grown significantly during the past 50 years (Bajracharya et al. 2007a). Accompanying this increase in the number and size of glacier lakes is an increased concern over the potential impact of GLOF events (Ives et al. 2010; Shrestha and Aryal 2011). The appearance and danger posed by glacier lakes in this region has prompted calls for assessments of the increasing risk to communities downstream of the lakes, and in some cases implementation of risk reduction actions (e.g., at Tsho Rolpa, and proposed for Imja Lake) (RGSL 2003; UNDP 2013). The Khumbu region of Nepal (Figure 1) has experienced two GLOF events in recent years--Nare in 1977 and Dig Tsho in 1985--both of which caused several deaths and the loss of substantial downstream infrastructure (Buchroithner et al. 1982; Fushimi et al. 1985; Zimmermann et al. 1986; Vuichard and Zimmermann 1986, 1987; Hammond 1988; Ives 1986; Ives et al. 2010). Twelve new and/or growing lakes within the Dudh Kosi watershed of the Khumbu region have been designated as “potentially dangerous glacial lakes (PDGLs)” based on the use of time-lapse satellite imagery (Bajracharya et al. 2007a; Xu et al. 2007; Bolch et al. 2008; Watanabe et al. 2009).

Imja Lake, located in the Khumbu region of Nepal (27.9^{o} N, 86.9 ^{o} E, see Figure 1), has been investigated for more than 20 years (Armstrong 2010). The lake has experienced particularly rapid growth in area and volume since the early 1960’s, leading to concern over the risk of a catastrophic GLOF event. The lake is bounded on the east by the Imja glacier terminus, to the northeast by Lhotse-Shar glacier, on the north and south by lateral moraines, and to the west by an extensive outlet complex (Figure 2). It is dammed by a 600 m wide by 700 m long ice-cored outlet complex through which lake water discharges. Figure 2 shows the lake with the glacier on the right, the body of the lake in the middle, and the outlet on the left. By 2002, the lake had a volume of 35.8 million m^3 (Sakai et al. 2003). In 2012, Somos-Valenzuela et al. (2013b) estimated the lake to contain a volume of 60 million m^3, nearly twice the amount estimated a decade earlier. The lateral moraine troughs on each side of the lake act as gutters, trapping debris derived from avalanches (Hambrey et al. 2008). The Imja glacier still covers the area beneath the lake, and the melting of this ice has caused the lake bottom to lower in recent decades (Watanabe et al. 1995; Fujita et al. 2009; Somos-Valenzuela et al. 2013b).

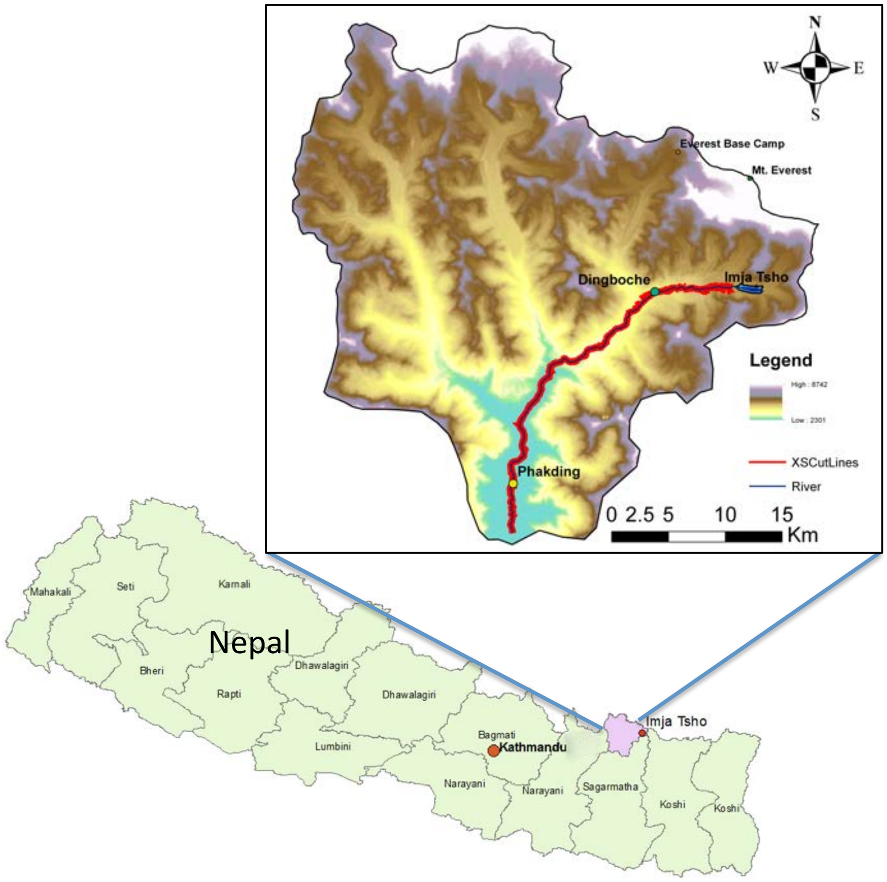

Figure 1. Location of Imja Lake in the Khumbu region of Nepal.

Imja Lake is thought by some to be among the most dangerous glacial lakes in the Khumbu region (Hammond 1988; Kattleman 2003; Ives et al. 2010; ICIMOD 2011), while others have concluded that the lake is relatively stable (Fujita et al. 2009; Watanabe et al. 2009; ICIMOD 2011). A GLOF event would result in significant downstream damage, e.g., upon the village of Dingboche and Phakding, 8 km and 33.6 km downstream of the lake's outlet, respectively. ICIMOD (2011) reported that the vulnerable population in village areas downstream of Imja Lake is about 96,767, and that as many as 7,762 people likely would be affected directly by a GLOF event.

In this paper, we present a characterization of the risk posed by Imja Lake, describe the development of a new hydraulic model for predicting the results of a potential GLOF from the lake in terms of the risk to downstream communities, discuss methods for reducing the GLOF risk, and present several alternatives to reduce that risk.


Figure 2. Imja Lake, September 2012

1.2. Characterizing Glacier Lake Risk

Several methodologies have been proposed for characterizing glacier lake risk (Grabs and Hanisch 1993; Mool et al. 2001a; Huggel et al. 2002; RGSL 2003; Huggel et al. 2004; Kääb et al. 2005, Bajracharya et al. 2007a; Richardson 2010; ICIMOD 2011; Emmer and Vilímek 2013), mostly following the basic framework suggested by Grabs and Hanisch (1992). The Grabs and Hanisch framework includes: (1) establishing a glacier lake inventory, (2) agreeing upon GLOF risk indicators, (3) estimating GLOF risk and the vulnerability of downstream infrastructure and communities, (4) comparing lake drainage alternatives and selecting one for implementation, (5) developing monitoring and early warning systems, and (6) performing further investigations as necessary.

The potential risk of a GLOF from Imja Lake has been investigated by numerous authors (Zimmermann et al. 1986; Ives 1986; Hammond 1988; Yamada and Sharma 1993; Watanabe et al. 1994; RGSL 2003; Hambrey et al. 2008; Watanabe et al. 2009; Fujita et al. 2009; Ives et al. 2010; Budhathoki et al. 2010; and ICIMOD 2011). Since the mid-1980s, Imja Lake has been the source of considerable disagreement regarding its GLOF potential and threat to downstream communities. Yamada and Sharma (1993), for example, describe Imja Lake as one of the most dangerous lakes in Nepal. During field visits, they observed the presence of glacier ice in the outlet, and that the moraines are comprised mostly of unconsolidated debris materials as well as ice-major indicators of risk, according to Grabs and Hanisch (1993). Watanabe et al. (1994, 1995) reported rapid melting of the debris-covered ice and significant changes in the outlet position of the lake. Reynolds Geo-Sciences Ltd. (RGSL) (2003) developed a vulnerability assessment scheme that was applied to Imja Lake, resulting in the conclusion that if a GLOF were to occur it would cause extensive damage for about 90 km downstream. Bajracharya et al. (2007a) called for urgent mitigation measures to reduce the GLOF risk of Imja Lake on the basis of its rapid growth. Based on data from 2000-2006, however, Hambrey et al. (2008) state that the risk of a moraine breach at Imja is very low because: (1) there is a low risk of calving waves, (2) the outlet is wide relative to its height, (3) that although the outlet has an ice-core that narrows as it melts, there exists sufficient ice-free moraine and freeboard to ensure a stable lake with a free-draining channel and low hydraulic gradient, and (4) changes to the moraine are gradual, so it can be easily monitored. After twenty years of study of Imja Lake, Japanese researchers likewise concluded that it was relatively stable (Watanabe et al. 2009; Fujita et al. 2009). Budhathoki et al. (2010) evaluated the hazard potential of Imja Lake based on the methodologies suggested by ICIMOD (2001), Huggel et al. (2002), and RGSL (2003). They concluded that there is a moderate risk of a GLOF from Imja Lake. Reporting on fieldwork performed in 2009, ICIMOD (2011) found the lake to be relatively stable but in need of regular monitoring.

The ICIMOD approach for characterizing glacier lake risk includes the lake and glacier characteristics listed in Table 1 (ICIMOD 2011), based primarily on physical criteria derived from remotely sensed data. Table 1 has been filled in for Imja Lake based on information available in 2013. Imja Lake exhibits19 of the 26 potentially dangerous glacial lake (PDGL) indicators on the list, suggesting that it is, indeed, a potentially dangerous lake. Table 2 presents the results of applying the empirical scoring method of Reynolds Geo-Sciences Ltd. (2003) to further refine the Imja Lake hazard estimate. The resulting score is 170 if conservative values are used, and 254 if worst-case values are used. Based on Reynolds Geo-Sciences Ltd.'s hazard rating scheme (Table 3), both of these values correspond to a "Very High" hazard, indicating that a GLOF could occur at any time.

Table 1. Dangerous Lake and Glacier Characteristics (adapted from ICIMOD 2011).

#	Description	Present at Imja Lake?
General characteristics		
1	Large size and rapid expansion	Yes
2	Increasing water level	Maybe
3	Intermittent activity of supra-glacial lakes	Yes
4	Position of lake in relation (adjacent) to moraines and associated glacier	Yes
Moraine dam characteristics		
5	Narrow crest	No
6	No drainage outflow or outlet not well formed	No
7	Steep moraine walls	Yes
8	Existence and stability of ice core and / or permafrost within moraine	Yes
9	Height of moraine	Yes
10	Mass movement (or potential for it) on the moraine slopes	Yes
11	Lake breached in the past and refilling	No
12	Seepage through moraine walls	Yes
Glacier characteristics		
13	Condition of associated glacier	Yes
14	Hanging glacier in contact with or close to lake	No
15	Large glacier area	Yes
16	Rapid glacier retreat	Yes
17	Debris cover on lower glacier tongue	Yes

18	Slope of glacier tongue	Yes
19	Presence of crevasses of ice from the glacier front	Yes
20	Ice bergs breaking off glacier terminus and floating into lake	Yes
Physical conditions and surroundings		
21	Potential rock fall and / or slide sites around the lake	Yes
22	Large snow avalanche sites immediately above	No
23	Neo-tectonic and earthquake activity	Yes
24	Climatic conditions, especially large inter-annual variations	No
25	Recent moraines of tributary glaciers that were previously part of a former glacier complex, and with multiple lakes that have been developed due to retreat of several glaciers in close proximity	Yes
26	Sudden advance of a glacier towards a lower tributary or main glacier that has a well developed frontal lake	No

Table 2. Lake Outburst Hazard Scoring System Applied to Imja Lake (adapted from RGSL 2003).

Category	**Factor**	**Score**				**Imja Score**	
		0	**2**	**10**	**50**	**Best case**	**Worst case**
Threshold	Volume of Lake	N/A	Low	Mod.	Large	50	50
Threshold	Lake level relative freeboard	N/A	Low	Mod.	Full	10	50
Threshold	Seepage evident through dam	None	Min.	Mod.	Large	50	50
Threshold	Ice-cored moraine dam	None	Min.	Partial	>Mod.	50	50
Trigger	Calving risk from ice cliff	N/A	Low	Mod.	Large	0	2
Trigger	Ice/rock avalanche	N/A	Low	Mod.	Large	0	2
Trigger	Supraglacial or englacial drainage	None	Low	Mod.	Large	0	0
	Compound risk (e.g., earthquake)	None	Slight	Mod.	Large	10	50
Total						**170**	**254**

Table 3. Hazard Rating Based on Empirical Scoring System (RGSL 2003).

Outburst likelihood score and hazard rating				
0	50	100	125	150+
Zero	Minimal	Moderate	High	Very High
		>>>>>> Outburst could occur at any time <<<<<<		

1.3 Previous modeling of GLOFs in the Khumbu region

A number of models have been applied to predicting the impact of GLOFs (Walder and Costa 1996; Chen et al. 1999; Chen et al. 2010; Cenderelli and Wohl 2001, 2003; Wang et al. 2008; Osti and Egashira 2009; Byers et al. 2013). The HEC-RAS unsteady flow model was used here, providing a practical program for assessing the downstream risk posed by a potential GLOF from Imja Lake. The limitations of one-dimensional models include a greater uncertainty in predicting the inundation extent of GLOF flows, and the fact that they cannot adequately represent large-feature incisions in debris-laden flows. Nevertheless, HEC-RAS has been applied successfully to GLOFs in the Nepal Himalaya on at least two previous occasions (Cenderelli and Wohl 2001, 2003; Osti et al. 2010). Bajracharya et al. (2007b) developed an Imja Lake GLOF model simulating the basin from the lake to about 45 km downstream of the outlet using 209 river cross-sections at 200 m intervals. The failure mode of the moraine was not specified, and may include either overtopping (which is unlikely to occur at Imja) or piping (a more likely possibility). This was a good first approximation of the behavior of a GLOF from Imja Lake. Dwivedi (2007) modeled the 1998 Tam Pokhari GLOF using the SOBEK flood model (Alkema et al. 2004) and a 40 m resolution DEM. Several breaching scenarios were simulated, and eroded sediments were not considered in the model. Shrestha et al. (2011) modeled a potential GLOF originating at Tsho Rolpa in the Rolwaling Valley of Nepal. The model included the GLOF breaching process from an assumed seepage failure. Laboratory experiments were conducted to verify the model and good agreement with model results were obtained.

Our model was developed specifically to assess the impact of a potential GLOF from Imja Lake and the risk to downstream communities, including Dingboche, the first major settlement downstream of the lake. In order to predict the behavior of a potential GLOF from Imja Lake, one-dimensional, unsteady simulations of GLOF scenarios were modeled using HEC-RAS. In addition, we analyzed the potential of recently proposed measures to provide protection for downstream communities, including one suggested by local community members, and developed a set of new alternatives to increase the level of protection. The use of siphons for lowering the level of Imja Lake is also explored, and recommendations for implementing this method are provided.

2. IMJA LAKE AND GLOF MODEL

2.1. Model Data

A 30 m *x* 30 m resolution Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) digital elevation model (DEM) (Tachikawa, 2011) was used to represent the topography of the watershed and provide a basis for delineating the basin and streams (Figure 1). The streamline of the Imja Khola and Dudh Kosi basins were delineated using the DEM and Google Earth. The modeled portion of the river has a length of 38.5 km from the lake outlet to a point 5 km downstream of the village of Phakding. Bathymetry of the lake was derived from the results of our 2012 sonar survey of Imja Lake (Somos-Valenzuela et al. 2013b). The stability of the HEC-RAS model is a function of the distance between the model cross sections and the time step used in the simulation. A time step of one second was used in the model. Interpolation between the initial, DEM-derived cross sections was used to generate cross sections with 2 m spacing in locations where greater solution stability was needed, resulting in a total of 16,990 cross sections in the model.

Imja Lake has a water surface elevation of about 5010 m. In the 2012 bathymetric survey of the lake, water depths of 20-60 m were measured near the western edge of the lake (outlet end) and 30-116 m deep near the eastern (glacier) end of the lake. The water available to drain from the lake in a GLOF event is now at least 33 million m^3 (Somos-Valenzuela et al. 2013b). The base of the outlet at the start of the valley below Imja Lake is about 4980 m.

2.2. Lake Outlet Breach Model

The outlet lake complex at Imja Lake is about 600 m wide (north to south) by 700 m long (west to east) by 30 m high. For the model, a piping breach is assumed to be the GLOF trigger, since this may be the most probable failure scenario and we observed extensive seepage from the base of the southern portion of the outlet dam in September 2011, May 2012, and September 2012. The other likely failure scenario would be from seismic activity that could potentially weaken the outlet structure, but this scenario has yet to be modeled.

The dam breaching process is modeled to start 10 minutes after the beginning of the simulation, and the full formation of the breach takes 1.65 hours (Table 4). The breach forms on the left side of the outlet (looking downstream) near the location of the observed piping (Figure 3). The roughness coefficient used in the model was 0.15 for the channel and 0.3 for the overbank areas for the entire river, consistent with the values found in Cenderelli and Wohl (2001) and Penjor (2008).

Table 4. Breach Plan for Imja Lake Outlet Dam

Item	Value
Breach bottom width and elevation	100 m, 4986 m
Breach formation time	1.65 hr after start of breach
Breach trigger	Piping, with coefficient 0.5
Initial piping elevation	4993 m amsl
Start of breach	10 min after start of breach

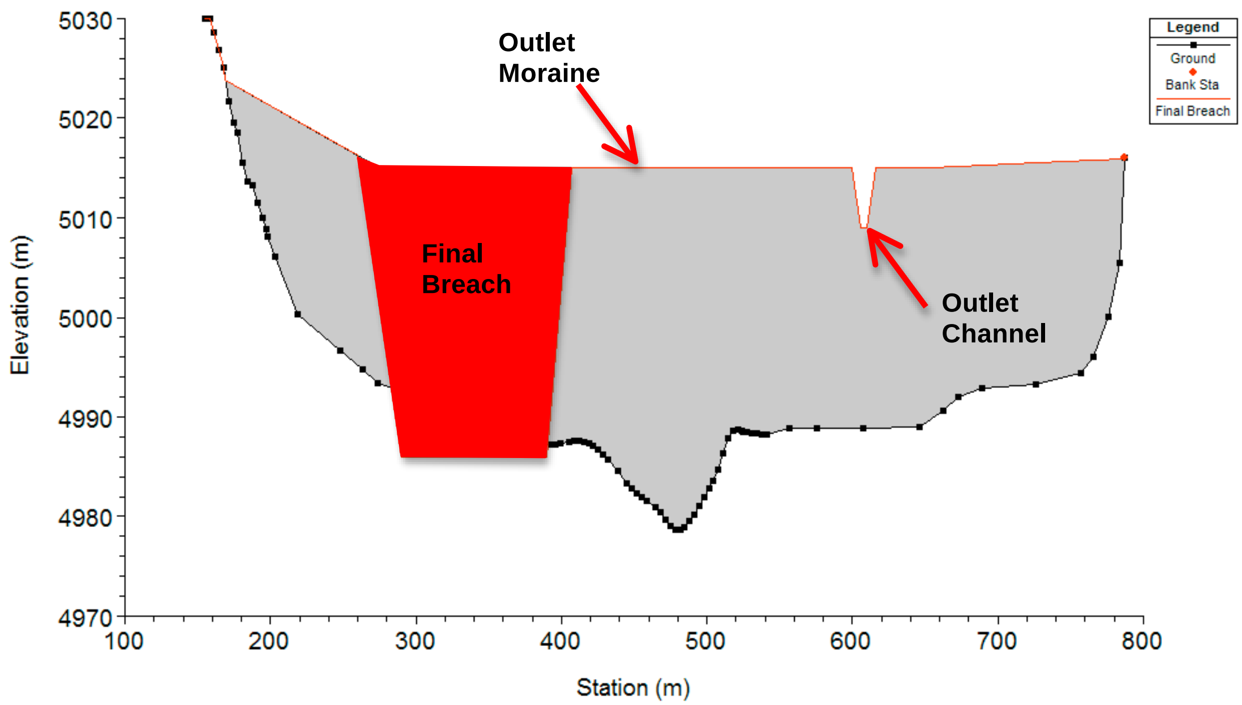

Figure 3. Outlet dam and potential breach at Imja Lake represented in HEC-RAS model.

2.3. Model Calibration

Recognizing the difficulties of model calibration in the absence of actual GLOF data, we used an empirical equation of the peak outflow from the breach and compared that to the value computed by the model. There are a number of similar breach peak-flow prediction equations in the literature (Wahl 2010). Wahl (2004) found the Froehlich (1995) equation to have the lowest uncertainty of the equations. Thornton et al. (2011) found that an expression relating the peak discharge (Q_{max} m^3/s) from the breach reduces the uncertainty while improving the prediction correlation

$$Q_{max} = 0.012V^{0.493}\, h^{1.205}\, L^{0.226} = 10{,}097 \text{ m}^3/\text{s} \qquad (1)$$

where V (m^3) is the volume of the lake, h (m) is the height of water behind the dam, L (m) is and the width of the crest of the dam. The volume (V) available for a GLOF from Imja Lake due to the piping breach illustrated in Figure 3 is 25.6 million m^3 (Somos-Valenzuela et al. 2013b), with a water height (h) of 25 m and a width (L) of 400 m. Froehlich (1995) developed an expression for the breach formation time, t (hr),

$$t = 0.00254V^{0.53}\, h^{-0.9} = 1.18 \text{ hr} \qquad (2)$$

In the model calibration procedure, t was varied in the HEC-RAS model until a peak discharge value of 10,022 m^3/sec was obtained in the model using $t = 1.65$ hr.

3. RESULTS

Several potential GLOF scenarios from Imja Lake were modeled, including a baseline scenario with no risk reduction measures. Table 5 and Figure 4 show the water elevation (stage) and flow rate at Dingboche. At Dingboche, the flood arrives 60 minutes after the breaching begins and peaks at 75 minutes, with a stage relative to the pre-GLOF level of 15.2 m and a flow of 8,383 m^3/s. The lag time between the peak flow at the breach and Dingboche is 20 minutes.

Table 5. GLOF Model Results at Selected Cross-Sections in the Imja Khola and Dudh Kosi.

Station	Distance from outlet (km)	Pre-GLOF Stage (m)	Arrival time (min)*	Peak Stage (m)	Relative Peak Stage (m)	Peak Time (min)*	Peak Flow (m^3/s)
Imja Lake outlet	0	4,979	0	4,991	11.7	55	10,022
Dingboche village	8.4	4,353	70	4,368	15.2	75	8,383
Phakding village	33.6	2,619	150	2,632	13	165	4,056

* time after start of breach at 10 minutes.

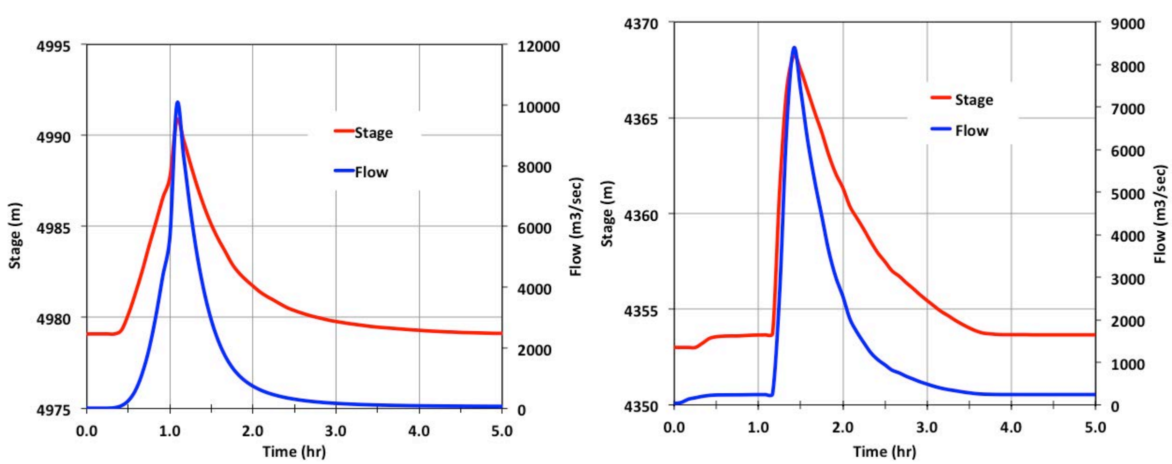

Figure 4. Left: Hydrograph at Imja Lake. Right: Hydrograph at Dingboche, 8.4 km downstream of Imja Lake outlet.

The main proposed alternative for reducing risk from Imja Lake is deepening the outlet channel of the lake in order to lower the water level by 3 m (UNDP 2013). To examine the potential risk reduction for downstream communities if such a plan, or one of several variations, were to be implemented, the Imja GLOF model was run with lake levels 3, 10, and 20 m lower than the baseline (5010 m). Table 6 shows the model results for each of the lake lowering scenarios. Lowering the lake 3 m results in a 5.2 percent reduction in the peak stage at Dingboche and 7.4 percent at Phakding. In contrast, lowering the lake 10 m results in an almost 34.4 percent reduction at Dingboche and 27.0 percent at Phakding, and lowering 20 m results in a 66.7 percent reduction at Dingboche and 59.7 percent at Phakding.

While no agreed upon set of risk indicators exists for Imja Lake, the definition of GLOF risk was discussed in consultations with community members in Dingboche in September 2012. The risk of a GLOF didn't exist 30 years ago, and their vulnerabilities stem from the location of their homes and farms relative to the flood plain. For them, risk is having their farms or homes flooded, a prospect that they want either reduced or eliminated. To evaluate the feasibility of proposed risk reduction alternatives, scenarios that reduce the peak flood stage at Dingboche or Phakding to less than 10 m above the pre-GLOF water level will likely reduce the risk of overtopping terraces with agricultural fields. Based on the model results, lowering the lake 20 m (highlighted in grey in Table 6) is the only scenario that leads to this level of protection for the communities.

Table 6. GLOF Model Results at Dingboche and Phakding when Imja Lake is Lowered 3, 10 or 20 m.

Lake Lower (m)	Flood Arrival Time (hr)	Flood Peak Time (hr)	Flood Peak Flow (m^3/s)	Flood Peak Stage (m)	Flood Relative Peak Stage (m)	Relative Peak Stage Reduction* (%)
	Dingboche					
3	1.17	1.42	7,354	4,367	14.4	5.2
10	1.17	1.42	3,628	4,363	10.0	34.4
20	1.67	2.08	1,107	4,358	5.1	66.7
	Phakding					
3	2.75	3.00	3,491	2,631	12.0	7.4
10	3.00	3.42	2,115	2,629	9.5	27.0
20	4.00	4.83	707	2,625	5.2	59.7

* referenced to the peak stage reported in Table 5

Dingboche community members also advised us that there might be a suitable location for a flood control dam in the valley immediately below Imja Lake. The topography of the site—a lateral moraine truncated by the river to the north, bounded by steep hillslopes from the southern riverbank onwards--indicates that it might be possible to construct up to a 60 m tall dam at that location. Scenarios that included 20, 40, and 60 m dams were simulated along with lake lowering scenarios of 0, 3, 10 and 20 m, all assuming that the dam cannot be overtopped. The results of those simulations are shown in Table 7. From these results, it appears that there are 3 feasible alternatives: (1) no dam with 20 m of lake lowering, (2) 40 m dam with 10 m of lake lowering, and (3) 60 m dam with no lake lowering. Figure 5 shows the relative flood stage reduction at Dingboche as a result of lowering the lake 0, 3, 10, or 20 m and dams of 0, 20, 40 , or 60 m height. Figure 6 shows the resulting stage and flow at both Dingboche under these alternative conditions.

Table 7. GLOF Model Results at Dingboche when Imja Lake is Lowered 3, 10 or 20 m. Scenarios that do not overtop the dam and result in at least 10 m stage reduction.

Lake Lower (m)	Arrival Time (hr)	Peak Time (hr)	Peak Stage (m)	Relative Peak Stage (m)	Relative Reduction (%)
	20 m dam				
0	1.25	1.42	4,368	15.2*	0
3	1.25	1.42	4,367	14.4*	5.8
10	1.25	1.50	4,362	9.5*	37.7
20	1.83	2.17	4,357	3.7	75.6
	40 m dam				
0	1.17	1.58	4,365	12.1	20.3
3	1.17	1.67	4,364	10.9	28.7
10	1.25	2.17	4,359	6.4	57.9
20	3.0	3.08	4,353	0.0	100.0
	60 m dam				
0	1.25	1.75	4,362	8.7	43.2
3	1.33	2.17	4,359	5.8	62.2
10	0.5	2.25	4,353	2.80	82.0
20	-	-	-	-	-

* Dam was overtopped.

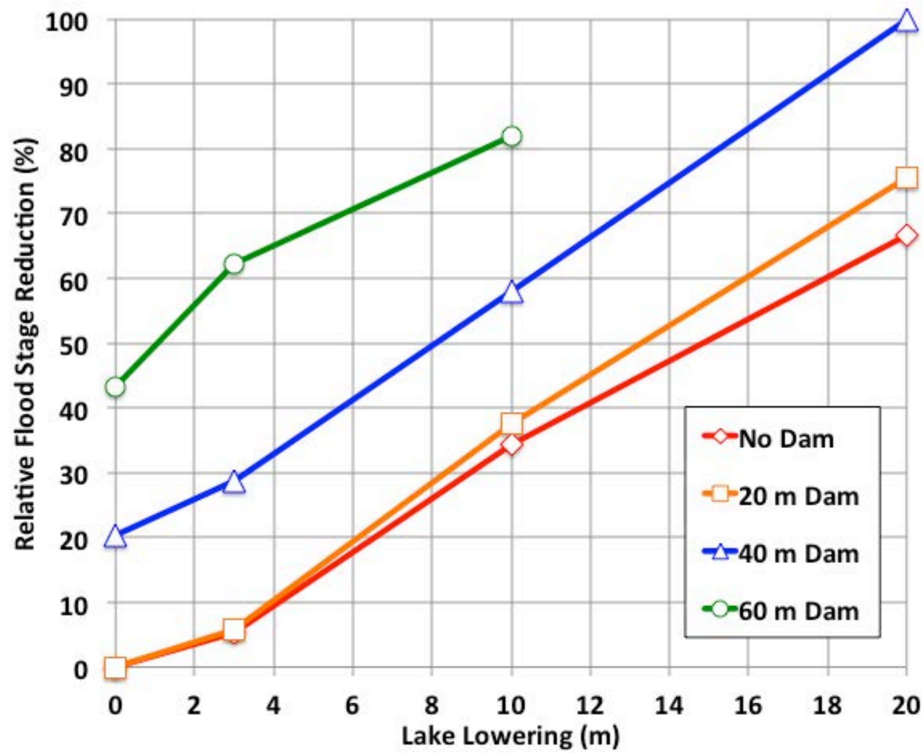

Figure 5. Relative flood stage reduction at Dingboche as a result of lowering Imja Lake 3, 10 or 20 m and dams of 0, 20, 40 or 60 m.

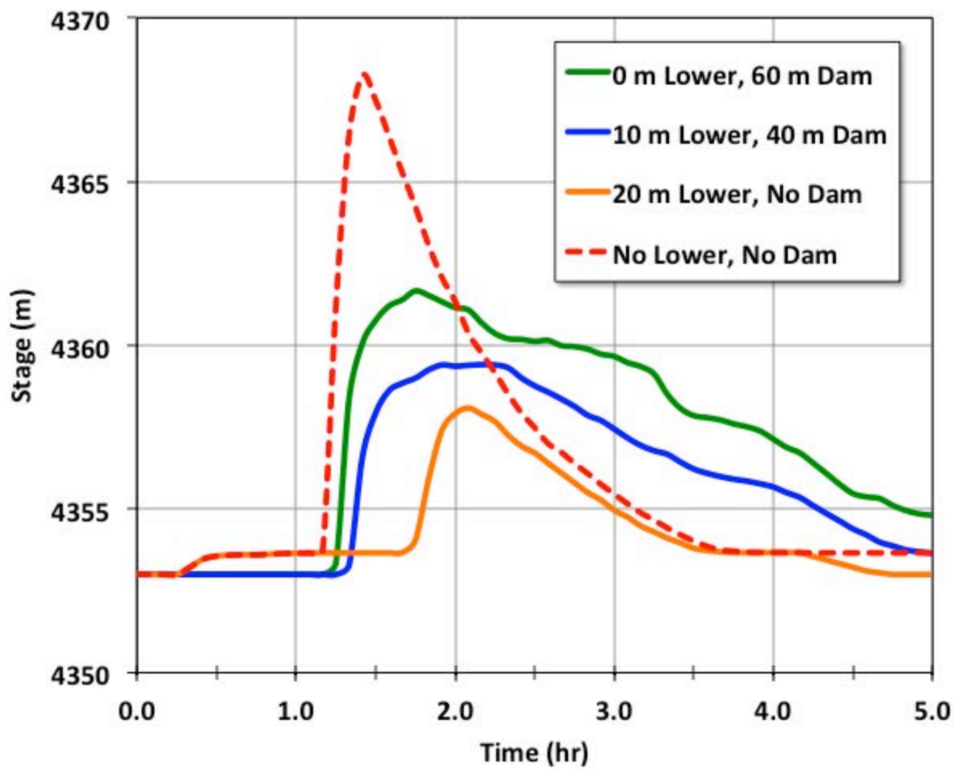

Figure 6. Feasible alternatives for risk reduction at Dingboche: (green) 3 m lake lowering with 60 m dam; (blue) 10 m lake lowering with 40 dam; and (orange) 20 m lake lowering with no dam.

4. DISCUSSION

4.1. Potential GLOF Triggers at Imja Lake

Kattleman and Watanabe (1998) discuss the GLOF triggers at Imja Lake: (1) surge waves generated by ice or rock avalanches into the lake that overtop the dam; (2) slow melting of the ice core within the dam; (3) seepage and piping through the dam; and (4) progressive thinning of the moraine by landslides and earthquakes.

Surge waves from rock and ice avalanches into Imja Lake from the surrounding high mountain peaks do not appear to be a danger at the present time because of the wide valley configuration surrounding the lake, and the distance of the existing up-glacier end of the lake from the mountains (Watanabe et al. 2009; Hambrey et al. 2008). We observed prominent seepage through two locations on the face of the outlet in September 2011, and in May and September 2012. This suggests that a piping trigger may be a significant risk at Imja Lake, especially in conjunction with an earthquake. Kattelmann and Watanabe (1997, 1998) list earthquakes as a potential Imja GLOF trigger because of the high seismicity of the region. An earthquake of sufficient strength to cause deformation of the moraine material, resulting in a piping failure of the moraine because of increased seepage, may in fact be the highest risk trigger for an Imja Lake outburst flood.

4.2. Potential Risk Reduction Measures for Imja Lake

4.2.1. Previous Recommendations for Lowering Imja Lake

Kattleman and Watanabe (1998) note that the methods of glacial lake control include the relocation of people and assets from the flood path, strengthening the outlet, reinforcing the outlet, and partially draining the lake. Of all the methods to increase glacial lake security, reducing lake volume appears to be the most reliable and successful, employed at over 40 dangerous lakes in Peru since the 1950s (Portocarrero 2013). Typically, the lake is lowered to a safe level using a drainage channel. A reinforced earthen dam is then constructed to replace the original unconsolidated moraine dam, such that if a surge wave does occur and the water level rises temporarily and overtops the dam, the dam will contain the excess water until the safe level is restored.

Siphons have been used on numerous lake lowering projects around the world as a way to stabilize lake water levels, e.g., Hualcán glacier lake (Lake 513) in Peru, where siphons were used to lower the lake by about 5 m with a capacity of about 0.5 m^3/s (Reynolds et al., 1998). Kattleman and Watanabe (1998) note that siphons from Imja Lake may be the most feasible alternative for lowering the lake. Grabs and Hanisch (1993) presented details of siphon methods for draining glacial lakes, showing that lowering glacier lakes at 5000 m by more than 5 m at a time is infeasible. Siphons were used to test the lowering of Tsho Rolpa glacial lake in Nepal during 1995-97, demonstrating that siphons can be used successfully at high altitude in freezing winter conditions (Rana et al. 2000).

Regardless of the risk reduction alternative, the question of to how to safely lower the lake remains. For example, siphons may be used to lower the lake level progressively in conjunction with excavation along the outlet of Imja Lake. In this way, siphons would be used to lower the lake a few meters, then excavate the channel, and continue this sequence until the desired lake level is reached.

4.2.2. Outlet Channel.

Strengthening and deepening the outlet of Imja Lake may be the best alternative for controlling the lake level. The lake lowering method proposed in the UNDP project is to excavate the existing outlet channel of the lake (near the end of the outlet lake complex) to increase its depth and thus discharge from the lake outlet, thereby lowering the lake level (Maskey 2012). The difficulties of employing this method, however, include: (1) the possibility of encountering ice during the excavation, significantly weakening the moraine and possibly inducing a GLOF; and (2) the existence of small ponds in the outlet complex that are separated with shallow necks (with as little as 1.5 m depth) through which the lake water flows (Somos-Valenzuela et al. 2013b), which would prevent the draining of the lake unless they were also excavated.

In 2012, we mapped the ice in the outlet area using Ground Penetrating Radar (GPR) and found that significant ice is indeed present (Somos-Valenzuela et al. 2013a). However, since the Imja Lake natural channel spillway is relatively stable (Watanabe et al., 2009), it may be possible to excavate and reinforce the spillway and the pathway through the outlet to increase the outflow and lower the lake. Additional and more detailed surveys are needed to determine if ice extends close to the natural spillway. If it does not, then there should be little problem in reinforcing and expanding the natural spillway. However, if the core is close to the spillway, then stabilization may be impossible in that location.

The UNDP project has used the experience and design of the lake lowering system at Tsho Rolpa as a model for Imja Lake. In that project, Tsho Rolpa was successfully lowered 3 m and an outlet channel constructed, but the original recommendation of the designers was to lower the lake by 20 m. The final 17 m of lowering, however, was never attempted (Rana et al. 2000; Mool et al. 2001b). As can be seen from the results presented here, following the Tsho Rolpa experience and lowering the lake level of Imja Lake by 3 m would not lead to a significant reduction in GLOF risk for downstream communities. The results shown above indicate that the lake should be lowered at least 20 m to ensure risk reduction for the communities downstream of the lake. The process of lowering the lake by 20 m, in increments of 3 to 4 m, using siphons and excavating the outlet channel to maintain the lower level is discussed in the next section.

4.2.3. Siphons.

In order to drain Imja Lake safely using siphons, it is necessary to combine siphoning and cutting of the outlet in a synchronized process. The level of the lake could be lowered by 20 m in 3 to 4 m increments from 5010 m to 4990 m. To achieve the first 3 m of lowering, the lake end of the siphon pipes need to be set in the lake about 700 m east of the lake outlet, and the downstream end of the pipes would be about 200 m west of the outlet face at a lower level in order to force the siphon to operate. The inlets of the pipes would be set 2 m beneath the lake surface and suspended by a buoy to maintain this submerged level during siphon operations. The siphons would be located along the outlet in order to obtain the minimum difference in elevation between the water (Point 1 in Figure 7) and the highest point of the system (Point 2 in Figure 7).

To lower the lake will require draining (1) the normal inflow to the lake; (2) the volume of the lake expansion during the time of drainage; and (3) the volume of the lake necessary to achieve the 3 m lowering per drainage cycle. Unfortunately, there are almost no measurements of the discharge from Imja Lake. Discharge from the lake was measured in May 2012 by Maskey (2012) using a salt-dilution method, and Somos-Valenzuela et al. (2013a) used a timed float method. In both cases the flow was found to be approximately 1 m^3/s. The lake area was 1.21 km^2 in September 2012, and it was increasing in area by 0.035 km^2/yr (Somos-Valenzuela et al. 2013b). This expansion will contribute 0.003 m^3/s to the flow if the lake is lowered 3 m.

The maximum lift of a siphon depends on altitude, flow velocity, and pipeline losses. As the siphon draws down the lake level, the absolute pressure at the highest point of the siphon approaches the vapor pressure of water and the siphon stops working if the absolute pressure reaches the vapor pressure. Point 2 in Figure 7 is the critical point of the siphon. If a working period of three months for siphoning, and two months for excavating and resetting the siphons for the next drainage period is assumed, then Table 8 shows the number of pipes needed to accomplish the lake lowering. In total, 13 pipes of 350 mm diameter are needed to lower the lake under these conditions.

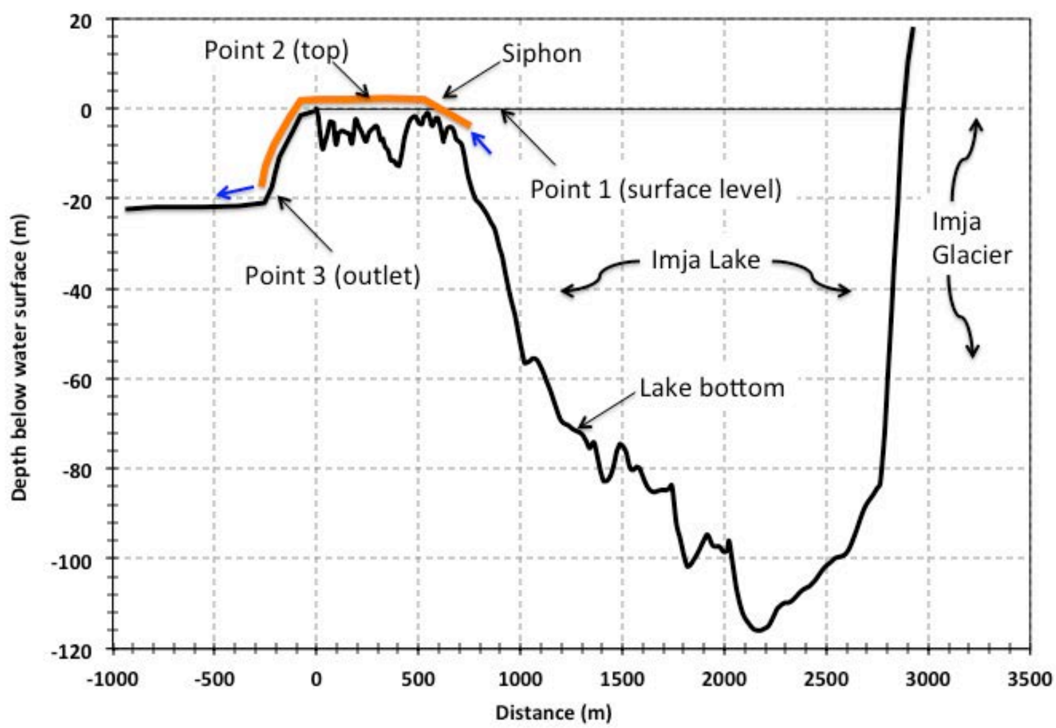

Figure 7. Imja Lake bottom elevation showing siphon system schematic at first stage.

Table 8. Pipes Needed to Lower Imja Lake in 3-Month Increments Using Siphons.

To drain Imja Lake	Lake water drained	Flow	Pipes needed		
	(Million m^3)	m^3/s	250 mm	300 mm	350 mm
To drain normal outflow + expansion					
Outflow and expansion	7.91	1.003	22	14	9
To lower the lake 20 m in 3 month increments					
Lake drainage	**11.44**	**1.45**	32	20	**13**

5. CONCLUSIONS

In this paper we illustrate some possible GLOF risk reduction measures for Imja Lake in Nepal and analyze their potential to reduce flood risk for downstream communities. The GLOF trigger mechanism considered here is a piping failure due to seepage in the face of the outlet dam. This could be a result of an increase of the currently observed seepage rate due to further melting of the ice in the moraine, or an earthquake weakening the moraine and causing an increase in the seepage. A model was developed to assess the impact of a potential GLOF from Imja Lake and its impact on downstream communities. The flooding impact on downstream communities due to the lake has been quantified, and several alternatives for reducing that impact have been illustrated along with their potential reduced flood levels. An alternative now under implementation by UNDP was considered, lowering the lake 3 m, and found not to provide significant flood reduction benefits to the downstream communities.

Alternative methods that do provide flood reduction benefits are suggested, including deeper draining of the lake and the use of downstream flood detention dams. The results indicate three potentially feasible alternatives for reducing flooding impact to the downstream communities: (1) no lowering of the lake and constructing a 60 m flood control dam, reducing the flood impact by 43.2 percent; (2) lowering the lake 10 m with 40 m dam, reducing the flood impact by 57.8 percent; and (3) lowering the lake 20 m with no dam, reducing the flood impact by 66.7 percent. All cases involving lowering the lake would require a coordinated sequence of siphoning to lower the water level in 3 m to 4 m increments, followed by outlet excavation to maintain the new level. The process would be repeated as needed to reach the desired lake level. The siphon system would require 13 pipes of 350 mm diameter to remove the natural flow and reduce the lake level.

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