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Assessing downstream flood impacts due to a potential GLOF from Imja Lake in Nepal

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Abstract

Glacial-dominated areas pose unique challenges to downstream communities in adapting to recent and continuing global climate change, including increased threats of glacial lake outburst floods (GLOFs) that can increase risk due to flooding of downstream communities and cause substantial impacts on regional social, environmental and economic systems. The Imja glacial lake in Nepal, with potential to generate a GLOF, was studied using a two-dimensional debris flow inundation model in order to evaluate the effectiveness of proposed measures to reduce possible flooding impacts to downstream communities by lowering the lake level. The results indicate that only minor flood impact reduction is achieved in the downstream community of Dingboche with modest (∼ 3 m) lake lowering. Lowering the lake by 10 m shows a significant reduction in inundated area. However, lowering the lake by 20 m almost eliminates all flood impact at Dingboche. Further downstream at Phakding, the impact of the GLOF is significant and similar reductions in inundation are likely as a result of lake lowering.

1 Introduction

Recent worldwide retreat of glaciers (WGMS, 2013) has been very evident in the Mt. Everest region of Nepal where glacial lakes continue to form and grow; significantly increasing the risk of glacier lake outburst floods (GLOFs) (S. R. Bajracharya et al., 2007; ICIMOD, 2011; Ives et al., 2010; Shrestha and Aryal, 2011). Many of these lakes are considered potentially dangerous (S. R. Bajracharya et al., 2007; Bolch et al., 2008; Watanabe et al., 2009; ICIMOD 2011). Therefore; risk and vulnerability assessments of communities and assets located downstream of glacial lakes in this region have become necessary. Remedial actions have been taken to reduce the risk of GLOF, in one case at Tsho Rolpa lake and another is under design at Imja Lake (Rana et al., 2000; UNDP 2013). In the region near Imja Lake, there have been 2 GLOFs in recent decades, Nare (1977) and Dig Tsho (1985), resulting in significant damage to farms, villages, trails and some loss of life (Buchroithner et al., 1982; Ives, 1986; Vuichard and Zimmermann, 1986).

Imja Lake, located in the Khumbu region (27.9° N, 86.9° E, Fig. 1), is bounded on the east by the Lhotse-Shar and Imja glaciers, on the north and south by lateral moraines, and to the west by a 700 m wide by 700 m long ice-cored outlet complex (Watanabe et al., 2009; Somos-Valenzuela et al., 2013). The lake, which did not exist in 1960, has experienced rapid growth in area and volume since then; by 2002 it had a volume of 35.8 ± 0.7 million m^3 (Sakai et al., 2007), and by 2012 the volume had increased to 61.7 ± 3.7 million m^3 (Somos-Valenzuela et al., 2014). The western, down-valley expansion has stabilized in recent years while the eastern expansion continues unabated (Watanabe et al., 2009) mostly through calving from the glacier terminus. Avalanche debris falling from surrounding high mountains and hanging ice is prevented from entering the lake by the high lateral moraines, which are separated from the surrounding mountains by several 10 s of meters (Hambrey et al., 2008). The bottom of the lake has continued to lower as the ice of the glacier beneath the lake melts (Watanabe et al., 1995; Fujita et al., 2009; Somos-Valenzuela et al., 2014).

The characterization of the risk of Imja Lake is somewhat controversial, with some researchers declaring it to be relatively dangerous (Hammond, 1988; Kattelmann, 2003; Ives et al., 2010), and others concluding that it may be stable (Fujita et al., 2009; Watanabe et al., 2009; ICIMOD, 2011). ICIMOD (2011) identified Imja Lake as one of six high-priority glacial lakes in Nepal that require detailed investigation, while other studies have stated that Imja Lake is safe (Fujita et al., 2013) or very low risk (Hambrey et al., 2008). These conflicting classifications are confusing and can be misleading to the general public and communities downstream, who are the stakeholders these studies are meant to assist. Imja Lake is among six glacial lakes identified in the Nepal National Adaptation Plan of Action (NAPA) as having at the most immediate risk of bursting (MoE, 2010). The United Nations Development Program (UNDP) is implementing the "Community Based Flood and Glacial Lake Outburst Risk Reduction Project" in an effort to reduce the possible risk to downstream communities posed by the lake.

According to the UNDP project strategy (UNDP, 2013), the "GLOF risks arising from Imja Lake will be significantly reduced by reducing the lake volume through an artificial controlled drainage system combined with a community-based early warning system." They recommend lowering the lake level by at least 3 m to achieve this risk reduction.

Dingboche is probably the most risk prone area from a potential Imja GLOF. The villages of Chukkung (∼ 4 km) and Dingboche (∼ 8 km) are the two nearest settlements from the lake. The former is located relatively off the Imja Khola (stream), so at less risk, whereas the latter is the largest settlement along the stream and it has extensive agricultural lands and buildings within 10–20 m elevation from the stream that will be flooded in the event of a GLOF unless flood prevention measures are taken.

In this paper we present a new, two-dimensional debris flow model for predicting the potential GLOF hazard from Imja Lake in terms of inundation depth in downstream communities and present a measure of uncertainty in the GLOF inundation predictions. We analyze four scenarios: current lake conditions, and three risk mitigation scenarios with the lake water level lowered 3, 10 or 20 m below the current level. Finally, we discuss possible methods for lowering the lake water level to reduce the GLOF hazard. To the authors' knowledge, this is the first attempt to quantify the impact that various flood control alternatives would have on potential GLOF damage in downstream villages.

2 Methodology

2.1 Data

To model the propagation of a GLOF from Imja Lake to the downstream community of Dingboche, we used two Digital Elevation Models (DEMs) for the Imja Lake GLOF model: (1) a 5 m × 5 m grid cell DEM of the Imja-Lhotse Shar glacier and the moraine surrounding the lake generated from 2006 ALOS imagery (Lamsal et al., 2011); and (2) a DEM extending from the lake to just below Dingboche derived using the method of Lamsal et al. (2011). These DEMs (Fig. 2) provide adequate resolution and terrain data for flooding and inundation modeling; however, they cover only 11 km of the river basin downstream from the lake. Expanded 5 m × 5 m DEM coverage downstream of Dingboche could be produced, but ALOS imagery was not available for this work. Instead, we used a lower resolution DEM for the region downstream of Dingboche to just below the village of Phakding. Initially a 30 m × 30 m resolution DEM was produced from Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER L1) data (Tachikawa, 2011). However, ASTER L1 data has too many unrealistic features such as many ponds between Imja Lake and Phakding that don't exist according to our field observations. Therefore, we decided to use the DEM created from 40 m interval contour topographic maps produced by B. Bajracharya et al. (2007). 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.

Roughness coefficients for eight categories of land cover in the basin were assigned using land cover maps derived from 2006 ASTER imagery for the Sagarmatha National park (Bajracharya and Uddin, 2010). These values agreed well with those that Cenderelli and Wohl (2001) calculated for the Imja Khola (0.15 and 0.30 for the riverbed and floodplain, respectively), and values that the Flo-2D manual (Flo-2D, 2012) recommends for the types of land cover found in the basin.

Somos-Valenzuela et al. (2014) conducted a bathymetric survey of Imja Lake in 2012 and estimated the lake volume was 61.7 ± 3.7 million m^3 and 34.1 ± 1.08 million m^3 of water could drain from the lake was if the lake surface elevation decreases 35 m from 5010 to 4975 m (the elevation of the valley floor below the lake). For the Imja Lake GLOF model, the lake bathymetry was combined with the DEM of the surrounding moraines and the glacier and used as input to the moraine dam breach model described below.

2.2 Moraine Dam Breach model

In order for a GLOF to occur from Imja Lake, a triggering event is nedded. Such triggers may include slow melting of the ice core within the damming moraine, seepage and piping through the dam and earthquakes (Kattelmann and Watanabe, 1998; Somos-Valenzuela et al., 2013). Other factors that may trigger a GLOF from Imja Lake include hydrostatic pressure or seismic effects causing a failure of the moraine dam. Hydrostatic pressure on the moraine may cause intense filtration and piping with potentially catastrophic consequences.

We observed seepage from the base of the southern portion of the damming moraine during five visits to the lake between 2011 and 2014. In September 2013 the seepage was measured using a tape measure and portable velocity meter (Global Water flow probe FP111 turbo prop positive displacement sensor with a range of 0.1–6.1 $\mathrm{m\,s^{-1}}$ and an accuracy of 0.03048 $\mathrm{m\,s^{-1}}$). At the seepage outlet, 2 sets of measurements were taken and an average flow of 0.005 $\mathrm{m^3\,s^{-1}}$ was calculated. In addition, 3 sets of flow measurements were made at the Imja Lake outlet (bridge over the Imja Khola) and an average flow of 2.2 $\mathrm{m^3\,s^{-1}}$ was calculated.

To model a potential moraine breach initiating a GLOF from Imja Lake, we use a combination of moraine breach analysis tools. First, the shape, final size, and failure time of the breach are estimated from empirical equations. Failure time is the time needed for complete development of the breach from the initial breakthrough to the end of lateral enlargement (Froehlich, 2008). Second, these parameters are used in a HEC-RAS dam breach model (USACE, 2010) to simulate the breach hydrograph, which is then used as input to a 2-D downstream inundation model.

There are a number of empirical dam breach equations in the literature (Wahl, 2010; Westoby et al., 2014). However, the equations developed by Froehlich (1995) were selected for use here because Wahl (2004) found these equations to have the lowest uncertainty among a large number of equations studied. Froehlich's equations (Froehlich, 1995) were used to predict breach width (B, m), failure time (t_f, h) and peak discharge

(Q_p, $\mathrm{m^3\,s^{-1}}$) are

$$B = 0.1803kV_\mathrm{w}^{0.32}h_\mathrm{b}^{0.19} \tag{1}$$

$$t_\mathrm{f} = 0.00254V_\mathrm{w}^{0.53}h_\mathrm{b}^{-0.9} \tag{2}$$

$$Q_\mathrm{p} = 0.607V_\mathrm{w}^{0.295}h_\mathrm{w}^{1.24} \tag{3}$$

where the moraine parameters in these equations are the breach height (h_b, m), the drainable water volume (V_w, $\mathrm{m^3}$), the depth of water above the breach invert at the time of failure (h_w, m), and overtopping multiplier k ($k = 1$ for no overtopping, and $k = 1.4$ for overtopping). The values of these parameters are shown in Table 1. The value of V_w in Table 1 was taken from the bathymetric survey results of Somos-Valenzuela et al. (2014). From a large database of dam breach cases, Wahl (2004) derived equations to calculate upper (P_u) and lower (P_l) bounds for the breach parameters

$$\{P_\mathrm{l}, P_\mathrm{u}\} = \left\{P_\mathrm{p} \times 10^{-e-2\mathrm{Se}}, P_\mathrm{p} \times 10^{-\overline{e}+2\mathrm{Se}}\right\} \tag{4}$$

where P_p is the predicted breach parameter value (B, t_f, or Q_p) estimated by Eqs. (1)–(3), e and 2Se are the mean prediction error and the uncertainty band (Wahl, 2004) (see Table 2).

Froehlich's equations provide estimates of the breaching parameters, but to simulate the downstream inundation, the full hydrograph of the breaching event is needed. To obtain full breach hydrographs (lower, predicted and upper) we use the HEC-RAS dam break model (USACE, 2010) with the breach width (B) and failure time (t_f) calculated from Eqs. (1) and (2). These hydrographs were adjusted to match the peak discharge (Q_p) values estimated from Eq. (3).

2.3 Inundation model

Flo-2D is used to calculate the flooding downstream of Imja Lake due to a potential GLOF with the breaching hydrograph discussed in the previous section. The model is suitable to simulate the propagation of the debris flow (Flo-2D, 2012), since the effects of sediments and debris have been shown to be very important factors in GLOF events (Osti and Egashira, 2009). Although the geometry of the grid within Flo-2D is two dimensional, the flow is modeled in eight directions and the model solves the one-dimensional Saint Venant equation independently in each direction. The continuity and momentum equations are solved with a central, finite difference method using an explicit time-stepping scheme. The total friction slope can be expressed as (Flo-2D, 2012; Julien, 2010; O'Brien et al., 1993)

$$S_\mathrm{f} = S_\mathrm{y} + S_\mathrm{v} + S_\mathrm{td} = \frac{\tau_\mathrm{y}}{\gamma_\mathrm{m} h} + \frac{K \eta \omega}{8 \gamma_\mathrm{m} h^2} + \frac{n^2 V^2}{h^{4/3}} \tag{5}$$

where S_y is the yield slope, S_v is the viscous slope, S_td is the turbulent-dispersive slope, τ_y is the Mohr-Coulomb yield stress, γ_m is the specific weight of the sediment mixture, K is a resistance parameter, η is the Bingham dynamic viscosity, V is the depth-averaged velocity, n is the Manning roughness coefficient. Rheological properties, η and τ_γ, are formulated as exponential functions of the sediment volume concentration c_v (Julien and Leon, 2000; Julien, 2010)

$$\eta = \alpha_2 e^{\beta_2 c_\mathrm{v}} \tag{6}$$

$$\tau_\gamma = \alpha_1 e^{\beta_1 c_\mathrm{v}} \tag{7}$$

where α_i and β_i are empirical coefficients defined by laboratory experiment (Flo-2D, 2009). Since we have very limited geological information for the study area, the values recommended by the Flo-2D manual for α_i and β_i are used ($\alpha_1 = 0.0765$, $\beta_1 = 16.9$, $\alpha_2 = 0.0648$ and $\beta_2 = 6.2$). Rickenmann (1999) and Julien and Leon (2000) recommend using a concentration of 50 % as an upper limit for debris flows when no other information is available and this value.

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3 Results

The Imja GLOF model described above was used to model four scenarios of a GLOF occurring from Imja Lake: current lake conditions with the water surface at 5010 m, and three flood mitigation scenarios with the lake water level lowered 3, 10 and 20 m, respectively. The flood mitigation scenarios represent possible lake lowering efforts starting with the current UNDP project to lower the lake at least 3 m. In case that scenario does not provide any significant flood reduction downstream at Dingboche, the other scenarios can provide some guidance as to how much farther the lake might need to be lowered to achieve reduced risk. It is important to note that no other studies have analyzed the potential benefits of lowering Imja Lake and that the selection of a preferred lake lowering alternative needs to be based on such an analysis as that presented here.

3.1 Moraine breaching model

3.1.1 Breach parameters

Table 3 shows the results of using Eqs. (1)–(3) and the moraine characteristics in Table 1 to calculate the lower bound, predicted, and upper bound values of the breaching parameters (B, t_f, and Q_p). The upper and lower bounds of the breaching parameters were calculated from Eqs. (4) and (5) using the prediction errors and uncertainty bands from Table 2. Lowering the lake level by 3 m does not result in a significant change in the failure time and only a 13.8 % decrease in the peak discharge. However, lowering the level by 10 m has a major impact on peak discharge, reducing it by 58.5 % and further lowering of the level to 20 m reduces the discharge by 73.8 %.

3.1.2 Breach hydrographs

Discharge hydrographs for potential moraine breaches at Imja Lake were computed using the HEC-RAS dam break module and the lower bound, predicted, and upper bound breach parameters under the current conditions scenario (see Table 4). The HEC-RAS hydrograph peak discharges were matched to the peak discharge values in Table 3 by adjusting the failure time within the range shown in the table. The predicted peak discharge is 8394 $m^3 s^{-1}$ (see Table 4 – Imja Lake) compared to 8274 $m^3 s^{-1}$ computed with Froehlich's equation, a difference of 1.4 %. The range of peak discharge (upper minus lower bound) is 14 728 $m^3 s^{-1}$ compared to 14 613 $m^3 s^{-1}$ computed by Froehlich's equation, about 0.8 % difference. These results indicate good agreement between the HEC-RAS computed hydrograph values and the empirical Froehlich equation values.

3.2 Inundation model

The Flo-2D inundation model was used to compute the results of the 4 potential Imja Lake GLOF scenarios. The first scenario considers the lake in its current condition with the lake level at 5010 m above mean sea level. Then alternatives with lake levels 3, 10, and 20 m lower than this were considered.

3.2.1 Current conditions scenario

The results (lower bound, expected value, upper bound) of modeling a potential GLOF from Imja Lake under current conditions are shown in Table 4 and Figs. 2–4 at Dingboche (at the cross section indicated in Fig. 4). Table 4 also shows the flood arrival time, peak time, peak stage, and flood peak discharge just downstream of Imja Lake and at Dingboche. Figure 2 shows the expected GLOF discharge hydrograph and bounds at Dingboche. The flood arrives at Dingboche 1 h after the breaching begins (range 0.6–1.9 h), peaks at 1.3 h (range 0.8–2.8 h) and is over after about 7 h. Figure 3 shows the flood stage at Dingboche (upper bound, expected value, lower bound). The highest expected flood stage is 22.4 m (range 18.4–26.4 m) and the peak flow is 7544 $m^3 s^{-1}$ (range 4208–13 248 $m^3 s^{-1}$). Figure 4a shows the expected inundation at Dingboche. The lower and upper bounds are also shown in Fig. 4b and c, respectively.

The inundated area at Dingboche was mapped in GIS and shows that, under the expected value simulation, most of the inundation is in the farming terrace areas and not the main lodges and other infrastructure along the primary trekking trail through the village (see Fig. 4, top image). With no lake lowering, about 9.4 ha of farmland will be inundated and 29 structures impacted (see Table 5, 0 m lowering scenario).

Further downstream at Phakding, the flooding also has an impact on potential flooding. At Phakding, the flood arrives 3.1 h (range 2.4–4.4 h) after the breaching begins and peaks at 3.2 h (range 2.6–4.7 h) with a peak discharge of 3412 $m^3 s^{-1}$ (range 3171–3473 $m^3 s^{-1}$) (see Fig. 5). The lag time between the peak flow at Imja Lake and the peak at Phakding is 2.2 h (see Table 4).

3.2.2 Lake lowering scenarios

A proposal to reduce the risk of a GLOF from Imja Lake that is currently (2014) under implementation is to lower the water level of the lake at least 3 m (UNDP, 2013). The Imja GLOF model was used to assess the potential flood reduction at Dingboche if such a plan were to be implemented. To this end, the model was run with lake levels 3, 10, and 20 m lower than the current conditions scenario level (5010 m). The results for these scenarios are shown in Table 5 and Figs. 6–8. Figures 6 and 7 show the hydrographs and flood stage, respectively, at Dingboche for the 0, 3, 10 and 20 m lake lowering scenarios. Figure 8 maps the inundation depth at Dingboche for the different lake lowering scenarios. Lowering the lake 3 m (Fig. 8a) results in a 2.7 % reduction in the peak flood depth at Dingboche (compared to the 0 m lowering scenario) with the peak flood height lowering 0.6 m (from 22.4 to 21.8 m). This flood height still leads to significant inundation of homes and farmlands. With the lake lowered by 3 m about 8.6 ha of farmland and 25 structures are impacted by the flooding. In contrast, lowering the lake 10 m (Fig. 8b) or 20 m (Fig. 8c) results in a 14 and 36 % flood height reduction, respectively, at Dingboche, with respective peak flood heights of 19.2 and 14.4 m. These scenarios lead to considerable reduction in inundated area, especially the 20 m lowering scenario where the flood stays mostly in the historic flood plain of the river, inundates little farmland and floods no structures. When the lake is lowered 10 m about 4 ha of farmland will be inundated and 18 structures impacted and at 20 m lowering about 1 ha of farmland will be inundated and 0 structures impacted. Additionally, the peak discharge is reduced by 6.5, 40.6 and 73.8 % as a result of lowering the lake by 3, 10 or 20 m, respectively (Table 5).

Further downstream at Phakding, the lake lowering scenarios have an impact on potential flooding as well (see Fig. 9). Lowering the lake 3 m results in a 13.9 % reduction of peak flow at Phakding. In contrast, lowering the lake 10 m results in 49.3 % reduction at Phakding, and lowering 20 m results in an 81.6 % reduction at Phakding (see Table 5).

4 Discussion

4.1 Comparison to previous Imja Lake GLOF modeling

B. Bajracharya et al. (2007) developed a water-flow GLOF model for Imja Lake that simulated flood flow in the Imja Khola and Dudh Kosi from the lake to about 45 km downstream of the outlet near Phakding. That one-dimensional model used a DEM derived from satellite data (30 m × 30 m grid cells) and one interpolated from 40 m contour maps (5 m × 5 m grid cells). This is the same DEM that we used for the reach from Dingboche to Phakding. The bathymetry of Imja Lake was taken from a 2002 survey indicating the total volume of the lake was 35.8 ± 0.7 million m^3 (Sakai et al., 2007), rather than the 61.7 ± 3.7 million m^3 total volume used in this study based on the more recent 2012 survey (Somos-Valenzuela et al., 2014). The US National Weather Service (NWS) BREACH model (Fread, 1988) was used to generate moraine breach hydrographs that were passed to a NWS FLDWAV model (Fread and Lewis, 1998) and routed downstream. Peak flows at the cross-sections of the FLDWAV model were input to a steady-state US Army Corps of Engineers HEC-RAS model (USACE, 2010) to predict inundation at key cross sections. ICIMOD (2011) extended the work of

B. Bajracharya et al. (2007) using additional field results to more accurately define the geotechnical parameters of the moraine. The lake bathymetry was updated from 2009 fieldwork with the total volume reported to be 35.5 million m^3 (ICIMOD, 2011). The moraine-breaching trigger was not specified and might be either overtopping or piping. The simulated breach depth was 30 m, the same as we used here.

We can compare the results of ICIMOD (2011) with those reported here, since this is being asked of the consultants working on the UNDP Imja Lake risk reduction project (UNDP, 2013). For the breaching process, ICIMOD reported a breaching time of 2.9 h with a peak discharge of 5817 $m^3 s^{-1}$; whereas, we calculate 1.01 h (range 0.38 to 7.32 h) and a peak of 8394 $m^3 s^{-1}$ (range 4272 to 19 000 $m^3 s^{-1}$). At Dingboche, ICIMOD reported a flood arrival of 3.1 h with a peak of 3000 $m^3 s^{-1}$ (estimated from Fig. 8.2, p. 65); whereas, we show flood arrival at 1 h (range 0.6–1.9 h) and a peak of 7544 $m^3 s^{-1}$ (range 4208–13 248 $m^3 s^{-1}$). At Ghat near Phakding, ICIMOD reported arrival at 4.2 h with a peak of 2300 $m^3 s^{-1}$, whereas, we calculate 3.1 h (range 2.4–4.4 h) with a peak of 3412 $m^3 s^{-1}$ (range 3171–3473 $m^3 s^{-1}$). The reason for the differences here is most likely the use of the significantly smaller Imja Lake volume in the ICIMOD calculations due to the bathymetry used. This causes faster propagation of larger flows downstream. In assessing the possibly reduced risk to downstream communities from implementing a lake lowering alternative, it is recommended that the latest estimates of the volume and bathymetry of Imja Lake be used, e.g., 2012 or later.

4.2 Options for Imja Lake risk reduction

To date there is no agreed upon set of hazard indicators for Imja Lake, or other potentially dangerous glacial lakes for that matter (Somos-Valenzuela et al., 2013); however, the definition of GLOF hazard from Imja Lake was discussed in consultations with community members in Dingboche in September 2012 and subsequently. The hazard of an Imja Lake GLOF did not exist 30 years ago, and the community members' vulnerabilities stem from the location of their homes and farms relative to the flood plain. For them, hazard is having their farms or homes flooded or washed away, a prospect that they want reduced and preferably eliminated (Somos-Valenzuela et al., 2013).

The feasibility of possible remedial actions at Imja Lake to reduce the hazard to downstream communities was evaluated. One scenario that appears to have significant risk reduction possibility is lowering the lake 20 m. Of course, there are other impacts of a GLOF from Imja Lake that will be felt downstream, in particular there are several stretches of the main trekking trail from Namche Bazar to Lukla that run quite close to the river and would be washed away, as they were in the 1985 Dig Tsho GLOF (Ives, 1986; Vuichard and Zimmermann, 1986). In addition some parts of villages along the trail have fields and houses near the river, and they may also be impacted. However, providing reduced flooding at Dingboche should also provide protection to many of the downstream areas as well. Lowering the lake by any amount will reduce the probability of GLOF occurrence for at least two reasons, the hydrostatic pressure on the moraine would be reduced and the top of the moraine would be wider and more difficult to breach. Consequently, reducing the GLOF's occurrence probability would decrease the hazard level downstream.

Of the methods to reduce glacial lake risk, e.g., relocation of people and assets from the flood path, strengthening the lake outlet (Kattelmann and Watanabe, 1998), the one that has been employed the most is lowering the lake level. This has been used at nearly 40 dangerous glacial lakes in Peru since the 1950s (Portocarrero, 2014). Typically, the lake is lowered to a safe level by siphoning or draining and then excavating the damming moraine and installing a drainage channel at the desired elevation. Often, a reinforced earthen dam is then constructed to replace the original unconsolidated moraine dam, such that if a surge wave overtops the dam it will contain much of the excess water and not fail from erosion (Somos-Valenzuela et al., 2013). In order to lower glacial lakes, siphons are often used, e.g., at Hualcán Lake (Lake 513) in Peru (Portocarrero, 2014). Lowering glacial lakes more than about 5 m is infeasible at altitudes of 5000 m, but greater lowering can be achieved using an incremental method as discussed below (Somos-Valenzuela et al., 2013).

The UNDP Imja Lake project suggests that lowering the lake "at least" 3 m will achieve significant risk reduction downstream (UNDP 2013), but there is no requirement to estimate the remaining risk when the lake is lowered to different levels (3, 10, 20 m). This work has attempted analyze this question. Siphons may be used at Imja Lake to progressively lower the level in 3–5 m increments followed by excavation of the lake outlet.

Previous studies have suggested deepening and strengthening the outlet of Imja Lake (Maskey, 2012). However, there are many difficulties in implementing this method. First, the natural flow of the outlet must be interrupted somehow in order to perform any excavation of the channel. In the siphoning method discussed above, the lake is lowered and then the outlet can be excavated to that level without needing to divert the outlet flow. One method that has been proposed is to build a coffer dam and divert water to flow over another part of the damming moraine and then excavate the existing outlet channel of the lake to increase its depth and discharge (Maskey, 2012). The difficulties of employing this method include: (1) possibly encountering ice during the excavation, significantly weakening the moraine and possibly inducing a GLOF, (2) diversion of the outlet flow might cause excessive erosion that could weaken the moraine and potentially lead to a GLOF, and (3) 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 might prevent the draining of the lake unless they were also excavated (Somos-Valenzuela et al., 2013). The difficulty of encountering buried ice exists in any method employing excavation of the damming moraine and the moraine must be examined in detail with geophysical methods before this can be done safely. The example of Tsho Rolpa is being used as a model lake lowering system for Imja Lake (UNDP, 2013). An outlet channel was constructed at Tsho Rolpa and 3 m lowering was achieved; however, the design called for lowering the lake by 20 m which was never attempted because of funding limitations (Rana et al., 2000; Mool et al., 2001). Our results show that lowering Imja Lake 3 m would not lead to a significant inundation reduction downstream. The lake should be lowered at least 10 m and probably 20 m to achieve significant hazard reduction. Lowering Imja 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 3 m lowering per drainage cycle (Somos-Valenzuela et al., 2013). Lake discharge was measured in May 2012 by a group from Kathmandu University using a tracer dilution method (Maskey, 2012) and by the authors using a timed float method (Somos-Valenzuela et al., 2013). In both cases the flow was found to be approximately 1 $\mathrm{m^3\,s^{-1}}$.

The authors again measured the flow with a flow meter in September 2013 and found the discharge to be approximately 2 $\mathrm{m^3\,s^{-1}}$ (see above for description of method). The lake area was $1.257 \pm 0.104\,\mathrm{km^2}$ in September 2012, and increasing by about 0.04 $\mathrm{km^2\,yr^{-1}}$ (Somos-Valenzuela et al., 2014). This will require 1.353 $\mathrm{m^3\,s^{-1}}$ of drainage to lower the lake 3 m during a 5 month period in the melt season using 13 siphon pipes of 350 mm diameter.

5 Conclusions

Methods for reducing the downstream inundation hazard from a GLOF originating at Imja Lake in Nepal were explored. A 2-dimensional debris flow model was developed to assess the downstream inundation. Inundation reducing scenarios were analyzed and an alternative under design, lowering the lake at least 3 m, was found not to have significant flood reduction benefits. The results indicate that the lake needs to be lowered about 20 m in order to completely reduce the impacts that a GLOF could have at Dingboche and further downstream. The results show that a GLOF occurring under the current lake conditions would result in inundation of much of the farming areas (about 9.4 ha and 29 structures impacted) at Dingboche but not the main lodges and other infrastructure along the primary trekking trail through the village. Lowering lake 3 m does not change this result much, but 10 m lowering reduces the impact substantially with about 4 ha of farmland and 18 structures impacted, and at 20 m lowering almost all impact at Dingboche is prevented. All cases involving lowering the lake would require a coordinated sequence of siphoning to lower the water level in 3 m increments, followed by outlet excavation to maintain the new level. The process would be repeated as needed to reach the desired lake level.

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References

Bajracharya, B. and Uddin, K.: Study of Land Cover Dynamics in Sagarmatha National Park and Buffer Zone, 10th Int. Symp. High Mt. Remote Sens. Cartogr., Kathmandu, Nepal, 12–19 September 2008, 125–132, 2010.

Bajracharya, B., Shrestha, A. B., and Rajbhandari, L.: Glacial lake outburst floods in the Sagartmatha regions: hazard assessment using GIS and hydrological modeling, Mt. Res. Dev., 27, 336–344, 2007.

Bajracharya, S. R., Mool, P. K., and Shrestha, B. R.: Impact of Climate Change on Himalayan Glaciers and Glacial Lakes Case Studies on GLOF and Associated Hazards in Nepal and Bhutan, International Centre for Integrated Mountain Development (ICIMOD), Kathmandu, 2007.

Bolch, T., Buchroithner, M. F., Peters, J., Baessler, M., and Bajracharya, S.: Identification of glacier motion and potentially dangerous glacial lakes in the Mt. Everest region/Nepal using spaceborne imagery, Nat. Hazards Earth Syst. Sci., 8, 1329–1340, doi:10.5194/nhess-8-1329-2008, 2008.

Buchroithner, M. F., Jentsch, G., and Wanivenhaus, B.: Monitoring of recent geoligical events in the Khumbu Area (Himalaya, Nepal) by Digital Processing of Landsat MSS Data, Rock Mech., 15, 181–197, 1982.

Cenderelli, D. A. and Wohl, E. E.: Peak discharge estimates of glacial-lake outburst floods and “normal” climatic floods in the Mount Everest region, Geomorphology, 40, 57–90, 2001.

Flo-2D: Flo-2D User’s Manual, Flo-2D Software, Inc., Nutrioso, AZ, 2009.

Froehlich, D. C.: Embankment dam breach parameters revisited, in: Proc., 1st Int. Conf. on Water Resources Engineering, American Society of Civil Engineers, New York, 14–18 August 1995, 887–891, 1995.

Froehlich, D. C.: Embankment dam breaches and their uncertainties, J. Water Res. Pl.-ASCE, 121, 90–97, 2008.

Fread, D. L.: BREACH, an Erosion Model for Earthen Dam Failures, United States National Weather Service, Hydrologic Research Laboratory, Silver Spring, Maryland, 58 pp., 1988.

Fread, D. L. and Lewis, J. M.: NWS FLDWAV Model, Theoretical Development, User Document, Silver Spring, MD, 1998.

Fujita, K., Sakai, A., Nuimura, T., Yamaguchi, S., and Sharma, R. R.: Recent changes in Imja Lake and its damming moraine in the Nepal Himalaya revealed by in-situ surveys and multi-temporal ASTER imagery, Environ. Res. Lett., 4, 045205, doi:10.1088/1748-9326/4/4/045205, 2009.

Fujita, K., Sakai, A., Takenaka, S., Nuimura, T., Surazakov, A. B., Sawagaki, T., and Yamanokuchi, T.: Potential flood volume of Himalayan glacial lakes, Nat. Hazards Earth Syst. Sci., 13, 1827–1839, doi:10.5194/nhess-13-1827-2013, 2013.

Grabs, W. E. and Hanisch, J.: Objectives and prevention methods for Glacier Lake Outburst Floods (GLOFs), snow and glacier hydrology, Proc. Of the Kathmandu Symposium, November, Kathmandu, Nepal, IAHS Publ. no. 218, 1993.

Hambrey, M. J., Quincey, D. J., Glasser, N. F., Reynolds, J. M., Richardson, S. J., and Clemmens, S.: Sedimentological, geomorphological and dynamic context of debris-mantled glaciers, Mountain Everest (Sagarmatha) region, Nepal, Quaternary Sci. Rev., 27, 2361–2389, 2008.

Hammond, J. E.: Glacial lakes in the Khumbu region, Nepal: an assessment of the hazards, unpublished, M.A. thesis, University of Colorado, Boulder, CO, 1988.

ICIMOD-International Centre for Integrated Mountain Development: Glacial lakes and glacial lake outburst floods in Nepal, International Centre for Integrated Mountain Development (ICIMOD), Kathmandu, Nepal, 2011.

Ives, J.: Glacial Lake Outburst Floods and Risk Engineering in the Himalaya, International Centre for Integrated Mountain Development (ICIMOD), Occasional Paper No. 5, Kathmandu, Nepal, 1986.

Ives, J. D., Shrestha, R. B., and Mool, P. K.: Formation of glacial lakes in the Hindu Kush-Himalayas and GLOF risk assessment, International Centre for Integrated Mountain Development (ICIMOD), Kathmandu, Nepal, 2010.

Julien, P. Y.: Erosion and Sedimentation, 2nd edn., Cambridge University Press, Cambridge, UK, 2010.

Julien, P. Y. and Leon, C. A.: Mud floods, mudlows and debris flows classification, rheology and structural design, in: Int. Work. Mudflows Debris Flows, Caracas, Venezuela, 1–16, 27 November–1 December 2000.

Kattelmann, R.: Glacial lake outburst floods in the Nepal Himalaya: a manageable hazard?, Nat. Hazards, 28, 145–154, 2003.

Kattelmann, R. and Watanabe, T.: Approaches to reducing the hazard of an outburst flood of Imja Glacier Lake, Khumbu Himal, in: Proc. of International Conference on Ecohydrology of High Mountain Areas, Kathmandu, Nepal, 24–28 March 1996, 359–366, UNESCO, 1998.

Lamsal, D., Sawagaki, T., and Watanabe, T.: Digital terrain modelling using corona and ALOS PRISM data to investigate the distal part of Imja Glacier, Khumbu Himal, Nepal, J. Mt. Sci., 8, 390–402, 2011.

Maskey, R. K.: Topographic Survey and Engineering Design of the Outlet Channel and Pre-feasibility Study for a Mini-Hydropower Generation Facility from Imja Lake, USAID ADAPT Asia-Pacific Support to UNDP/Nepal: Community Based GLOF and Flood Risk Reduction Project, Bangkok, United States Agency for International Development (USAID), 2012.

MoE – Ministry of the Environment: National Adaptation Programme of Action to Climate Change, Kathmandu, Nepal, 2010.

Mool, P. K., Bajracharya, S. R., and Joshi, S. P.: Risk Assessment of Lake Rolpa Glacial Lake along the Rolwaling and Tama Kosi Valleys Dolakha District, Nepal, International Centre for Integrated Mountain Development (ICIMOD), Kathmandu, Nepal, 2001.

O'Brien, J. S, Julien, P. Y., and Fullerton, W. T.: Two-dimensional water flood and mudlow simulation, J. Hydraul. Eng., 119, 244–261, 1993.

Osti, R. and Egashira, S.: Hydrodynamic characteristics of the Tam Pokhari Glacial Lake outburst flood in the Mt. Everest region, Nepal, Hydrol. Process., 23, 2943–2955, doi:10.1002/hyp.7405, 2009.

Portocarrero, C.: The Glacial Lake Handbook: Reducing Risk from Dangerous Glacial Lakes in the Cordillera Blanca, Peru, United States Agency for International Development, Washington DC, 2014.

Rana, B., Shrestha, A. B., Reynolds, J. M., Aryal, R., Pokhrel, A. P., and Budhathoki, K. P.: Hazard assessment of the Lake Rolpa Glacier Lake and ongoing remediation measures, J. Nepal Geological Society, 22, 563–570, 2000.

Reynolds, J. M., Dolecki, A., and Portocarrero, C.: The construction of a drainage tunnel as part of glacial lake hazard mitigation at Hualcán, Cordillera Blanca, Peru, Geological Society, London, Eng. Geol. Special Publications 1998, London, 15, 41–48, 1998.

Rickenmann, D.: Empirical relationships for debris flows, Nat. Hazards, 19, 47–77, 1999.

Sakai, A., Saito, M., Nishimura, K., Yamada, T., Iizuka, Y., Harada, K., Kobayashi, S., Fujita, K., and Gurung, C. B.: Topographical survey of end-moraine and dead ice area at the Imja Glacial Lake in 2001 and 2002, Bull. Glaciol. Res., 24, 29–36, 2007.

Shrestha, A. B. and Aryal, R.: Climate change in Nepal and its impact on Himalayan glaciers, Reg. Environ. Change, 11, S65–S77, 2011.

Somos-Valenzuela, M., McKinney, D. C., Byers, A. C., Rounce, D. R., and Portocarrero, C.: Modeling mitigation strategies for risk reduction at Imja Lake, Nepal, High Mountain Glacial Watershed Program, CRWR Online Report 13–06, Center for Research in Water Resources, University of Texas, Austin, 2013.

Somos-Valenzuela, M. A., McKinney, D. C., Rounce, D. R., and Byers, A. C.: Changes in Imja Tsho in the Mount Everest region of Nepal, The Cryosphere, 8, 1661–1671, doi:10.5194/tc-8-1661-2014, 2014.

UNDP – United Nations Development Programme: Community based glacier lake outburst and flood risk reduction in Nepal, Project Document, UNDP Environmental Finance Services, Kathmandu, Nepal, 2013.

USACE – U.S. Army Corps of Engineers: HEC-RAS River Analysis System Hydraulic Users Manual (Version 4.1), Hydrological Engineering Center, Davis, CA, 2010.

Vuichard, D. and Zimmermann, M.: The Langmoche flash-flood, Khumbu Himal, Nepal, Mt. Res. Dev., 6, 90–94, 1986.

Wahl, T. L.: Uncertainty of predictions for embankment dam breach parameters, J. Hydraul. Eng., 130, 389–397, 2004.

Wahl, T. L.: Dam Breach Modeling – an Overview Of Analysis Methods, Joint Federal Interagency Conference on Sedimentation and Hydrologic Modeling, 27 June–1 July 2010, Las Vegas, NV, 2010.

Watanabe, T., Kameyama, S., and Sato, T.: Imja glacier dead-ice melt rates and changes in a supra-glacial lake, 1989–1994, Khumbu Himal, Nepal: danger of lake drainage, Mt. Res. Dev., 15, 293–300, 1995.

Watanabe, T., Lamsal, D., and Ives, J. D.: Evaluating the growth characteristics of a glacial lake and its degree of danger of outburst flooding: Imja glacier, Khumbu Himal, Nepal, Norsk Geogr. Tidsskr., 63, 255–267, 2009.

Westoby, M. J., Glasser, N. F., Brasington, J., Hambrey, M. J., Quincey, D. J., and Reynolds, J. M.: Modelling outburst floods from moraine-dammed glacial lakes, Earth-Sci. Rev., 134, 137–159, doi:10.1016/j.earscirev.2014.03.009, 2014.

WGMS – World Glacier Monitoring Service: Preliminary Glacier Mass Balance Data 2010/2011, available at: http://www.wgms.ch/mbb/sum11.html (last access: 10 March 2014), 17 January 2013

Table 1. Moraine parameter values used in the breaching equations.

Parameter	Scenario			
	Current Conditions	Lake Lowering		
		3 m	10 m	20 m
Moraine height (h_d, m)	35	32	25	15
Breach height (h_b, m)	35	32	25	15
Water height (h_w, m)	35	32	25	15
Water volume above breach invert (V_w, million m^3)	33.5	29.5	22.4	12.5

Table 2. Prediction error and uncertainty bands for the Froehlich breaching equations.

Parameter	Mean Prediction Error (e)	Uncertainty Band (±2Se)
Breach Width (B, m)	0.01	±0.39
Failure Time (t_f, h)	−0.22	±0.64
Peak Discharge (Q_p, $m^3 s^{-1}$)	−0.04	±0.32

Table 3. Breach parameter expected values and uncertainty bands for four scenarios.

Scenario	Value Type	Breach Width B (m)	Failure Time t_f (h)	Peak Discharge Q_p ($m^3 s^{-1}$)
Current Conditions	Lower bound	36	0.38	4342
	Predicted	91	1.01	8274
	Upper bound	218	7.32	18 955
Lower 3 m	Lower bound	34	0.39	3742
	Predicted	86	1.02	7131
	Upper bound	206	7.39	16 336
Lower 10 m	Lower bound	30	0.42	2539
	Predicted	75	1.1	4838
	Upper bound	180	7.97	11 083
Lower 20 m	Lower bound	22	0.49	1135
	Predicted	56	1.28	2163
	Upper bound	134	9.27	4955

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Table 4. Inundation model expected values and uncertainty bands at Imja Lake, Dingboche and Phakding for current lake conditions.

Station	Value	Arrival Time (h)	Peak Time (h)	Peak Discharge ($m^3 s^{-1}$)	Peak Stage (m)
Below Imja Lake	Lower Bound	0.8	2.3	4272	12.1
	Predicted	0.3	1.0	8394	16.6
	Upper Bound	0.2	0.5	19 000	33.4
Dingboche	Lower Bound	1.9	2.8	4208	18.4
	Predicted	1.0	1.3	7544	22.4
	Upper Bound	0.6	0.8	13 248	26.4
Phakding	Lower	4.4	4.7	3171	
	Predicted	3.1	3.2	3412	
	Upper	2.4	2.6	3473	

Table 5. Inundation model results at Dingboche and Phakding for lake lowering scenarios under current conditions.

Lake Lowering Scenario (m)	Arrival Time (h)	Peak Time (h)	Peak Discharge ($m^3 s^{-1}$)	Peak Discharge Reduction* (%)	Peak Depth (m)	Peak Depth Reduction* (%)	Farm Area Inundated (m^2)	Buildings Inundated (#)
				Dingboche				
0	1.0	1.3	7544	0	22.4	0	93 650	29
3	1.1	1.5	7053	6.5	21.8	2.7	86 262	25
10	1.3	1.6	4479	40.6	19.2	14.3	40 226	18
20	1.3	1.8	1975	73.8	14.4	35.9	10 686	0
				Phakding				
0 m	3.1	3.2	3412	0				
3 m	3.2	3.5	2937	13.9				
10 m	3.9	4.2	1730	49.3				
20 m	5.8	6.1	629	81.8				

[*] Relative to the peak value for 0 m lake lowering.

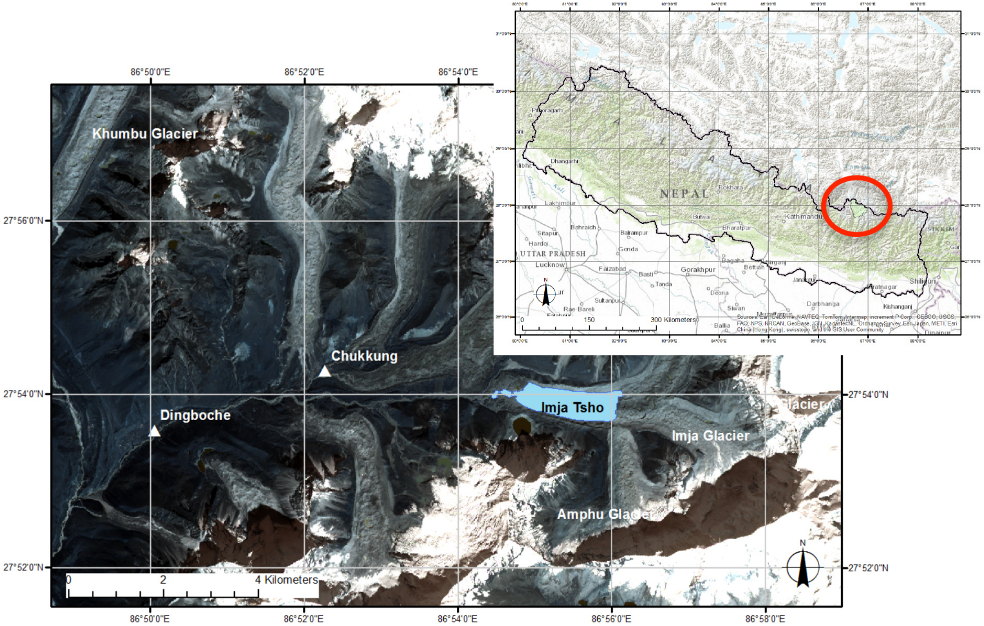

Figure 1. Location of Imja Lake in the Khumbu region of Nepal. Source: Nepal map – ESRI, World Imagery (2014); Image – Google Earth (2014).

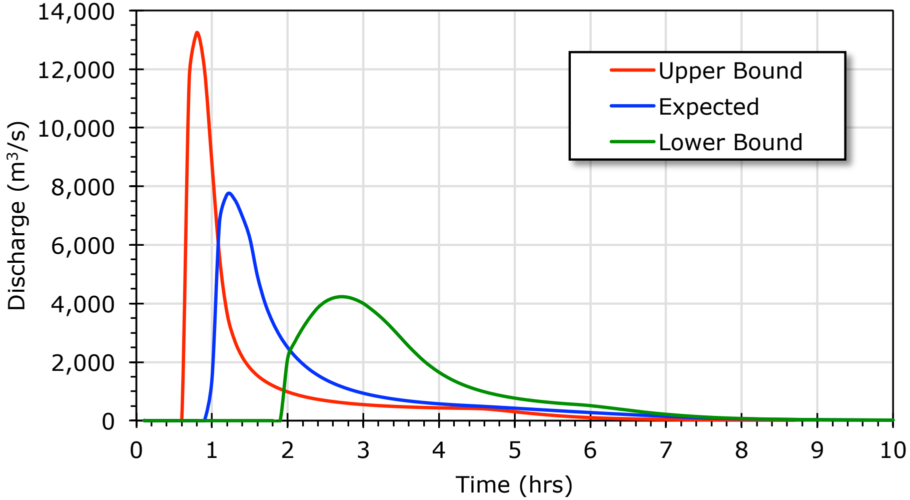

Figure 2. Upper bound, expected and lower bound GLOF hydrograph at Dingboche under current lake conditions.

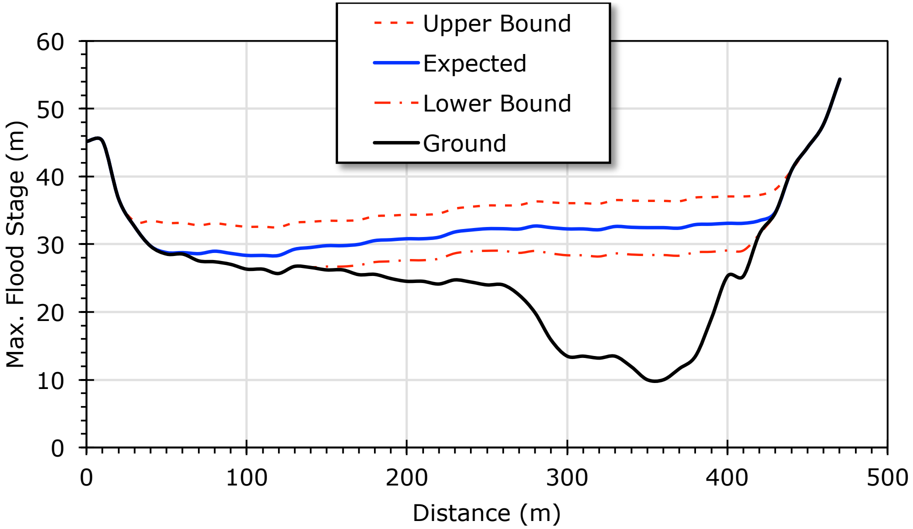

Figure 3. Upper bound, expected and lower bound GLOF flood stage at Dingboche (cross section shown in Fig. 4) under current conditions.

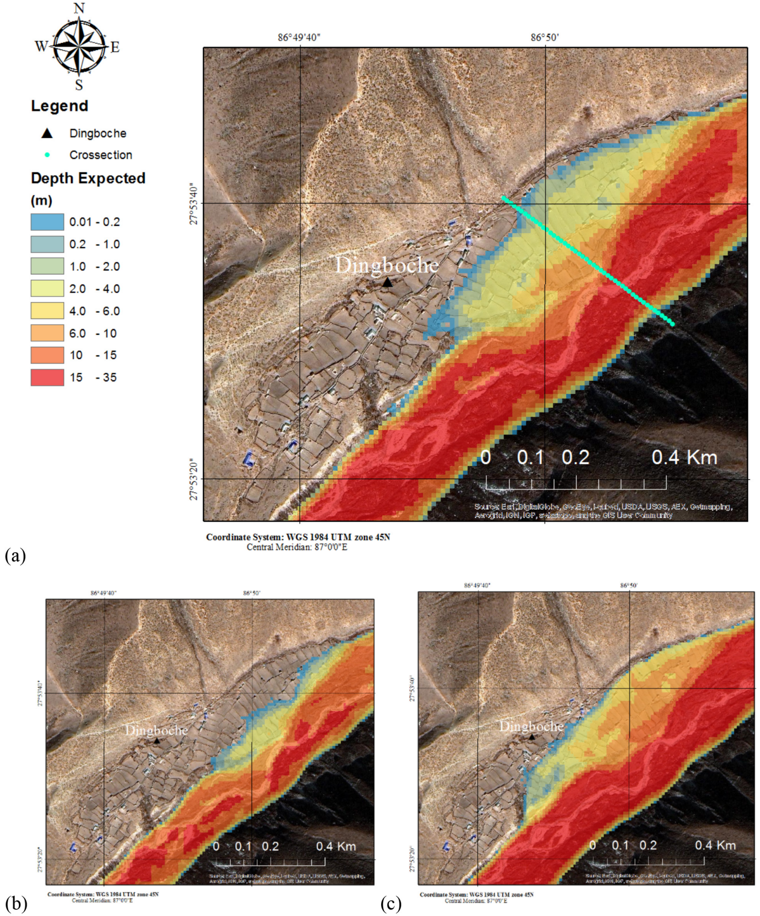

Figure 4. Inundation at Dingboche under current lake conditions: **(a)** expected inundation and the location of the cross section where the different scenarios are compared; **(b)** lower bound; and **(c)** upper bound of the possible inundation.

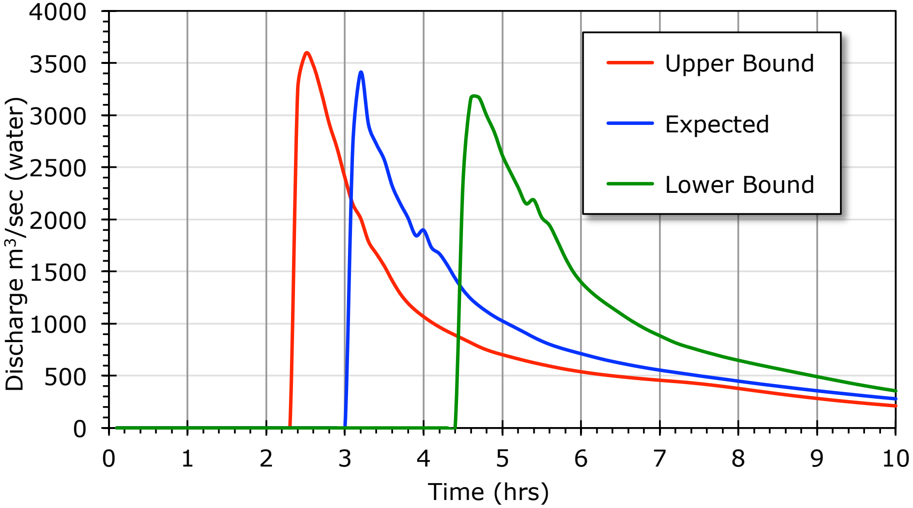

Figure 5. Upper bound, expected and lower bound GLOF hydrograph under current conditions at Phakding.

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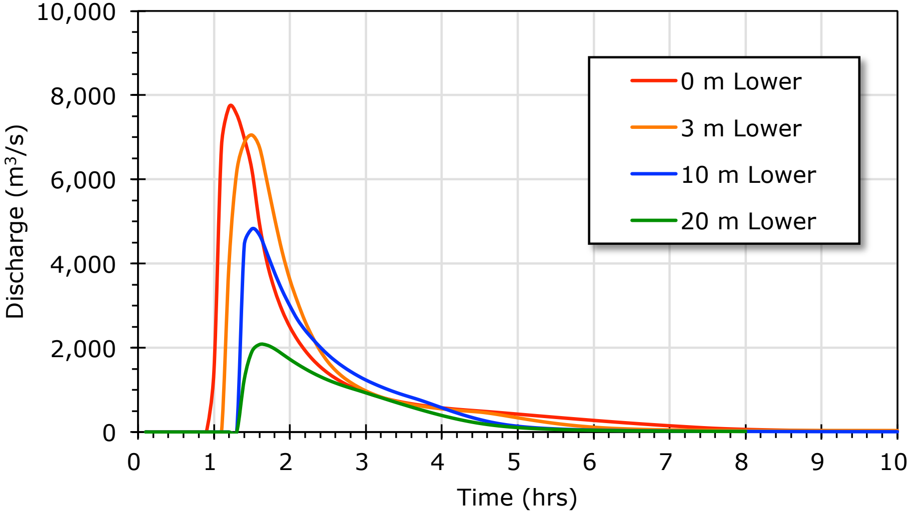


Figure 6. GLOF hydrographs at Dingboche under current lake conditions for 0, 3, 10 and 20 m lake lowering scenarios.

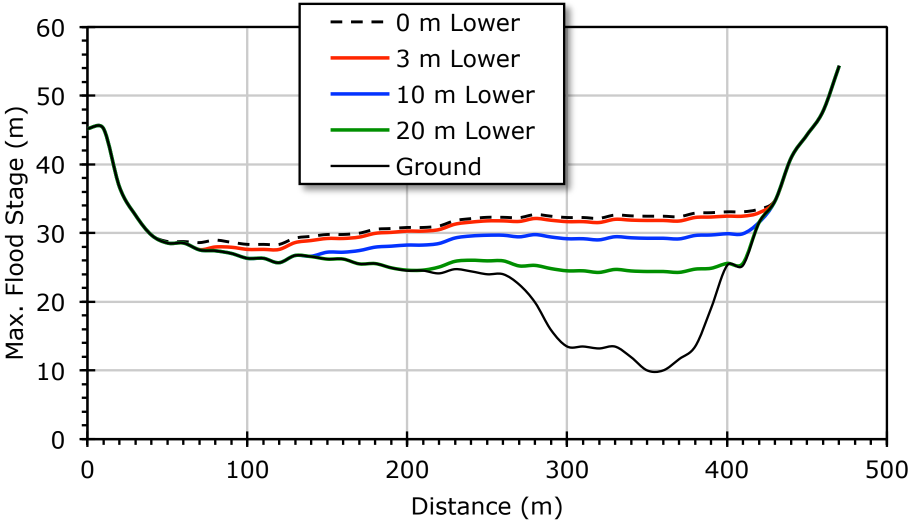
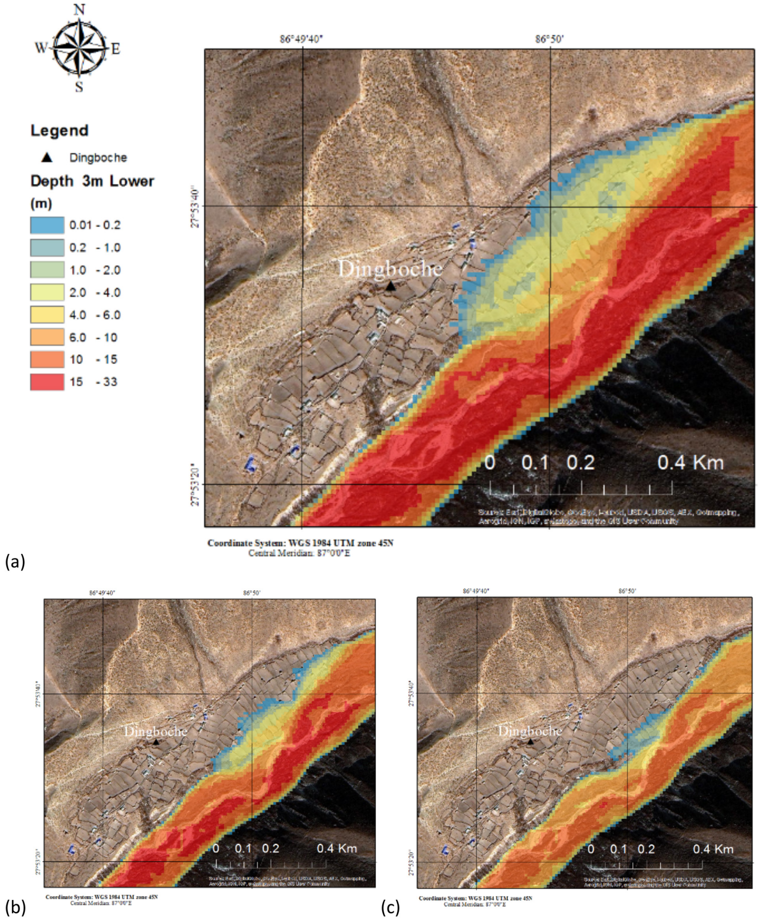


Figure 7. GLOF flood stage at Dingboche under current lake conditions for 0 m (Expected), 3, 10 and 20 m lake lowering scenarios.



(a)

(b)

(c)

Figure 8. Inundation depth at Dingboche under current lake conditions: **(a)** 3 m lake lowering; **(b)** 10 m lake lowering; and **(c)** 20 m lake lowering.

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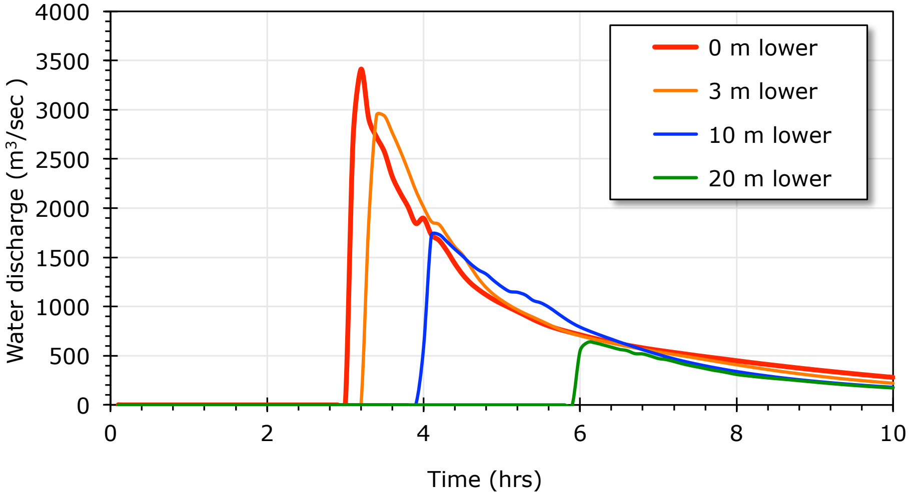

Figure 9. GLOF hydrographs at Phakding under current conditions for 0, 3, 10 and 20 m lake lowering scenarios.