

**HESS-2015-512-Discussions**

Modeling glacial lake outburst flood process chain: the case of Lake Palcacocha and Huaraz, Peru

M. A. Somos-Valenzuela, R. E. Chisolm, D. S. Rivas, C. Portocarrero, and D. C. McKinney

**RESPONSE TO THE EDITOR DECISION 22-MAY-2016****GENERAL COMMENTS****General Comment 1:**

**GC-1:** Section 1.2 (“Introduction to glacial lake hazard process chain modeling”), not all mentioned references are explicitly related to the methodology used in the study. It is not clear which achievements of the previous models and methods are utilized, which drawbacks need to be improved in this study and so on.

**Response to GC-1:** The paper has been revised to respond to this comment. In Section 1.2, the unrelated references have been removed and the achievements of previous methods and their drawbacks have been highlighted as well as where and how improvements have been made in this work.

**New text in Section 1.2:**

“Impulse waves resulting from the impact of an avalanche with the lake were simulated with a three-dimensional hydrodynamic model, FLOW3D (Flow Science, 2012). Much of the work in impulse wave generation, propagation and run-up has been focused on empirical models that replicate wave characteristics based on laboratory observations (Kamphuis and Bowering 1970; Slingerland and Voight, 1979, 1982; Fritz et al., 2004; Heller and Hager, 2010); numerical simulations have been limited to simplified two-dimensional SWE simulations (Rzadkiewicz et al., 1997; Biscarini, 2010; Cremonesi et al., 2011; Ghozlan et al., 2013; Zweifel et al., 2006). However, the 2D SWE representations do a poor job of modeling wave generation and propagation because vertical accelerations are important and cannot be neglected for slide-generated waves (Heinrich, 1992; Zweifel et al., 2006). Analytical calculations of wave run-up and overtopping typically consider simplified lake geometries (e.g., uniform water depth and constant slope of the terminal moraine) that do not necessarily hold true in natural reservoirs (Synolakis, 1987, 1991; Muller, 1995; Liu et al., 2005). The limitations of empirical and 2D SWE models for simulating lake dynamics leave an opening for a more robust approach. Therefore, a fully 3D non-hydrostatic model (FLOW 3D) was used in this paper to simulate the wave generation, propagation and overtopping. “

**GC-2:** Move the following from 3rd (Methodology) Section to Introduction. P.9, line 21 – P.10, line 5 - short concrete review of the lake simulation approaches

**Response to GC-2:** We appreciate the suggestion and we have implemented it by moving the text to the Introduction and merging it with the existing text there.

Revised text in Section 1.2:

“Impulse waves resulting from the impact of an avalanche with the lake were simulated with a three-dimensional hydrodynamic model, FLOW3D (Flow Science, 2012). Much of the work in impulse wave generation, propagation and run-up has been focused on empirical models that replicate wave characteristics based on laboratory observations (Kamphuis and Bowering 1970; Slingerland and Voight, 1979, 1982; Fritz et al., 2004; Heller and Hager, 2010); numerical simulations have been limited to simplified two-dimensional SWE simulations (Rzadkiewicz et al., 1997; Biscarini, 2010; Cremonesi et al., 2011; Ghozlani et al., 2013; Zweifel et al., 2006). However, the 2D SWE representations do a poor job of modeling wave generation and propagation because vertical accelerations are important and cannot be neglected for slide-generated waves (Heinrich, 1992; Zweifel et al., 2006). Analytical calculations of wave run-up and overtopping typically consider simplified lake geometries (e.g., uniform water depth and constant slope of the terminal moraine) that do not necessarily hold true in natural reservoirs (Synolakis, 1987, 1991; Muller, 1995; Liu et al., 2005). The limitations of empirical and 2D SWE models for simulating lake dynamics leave an opening for a more robust approach. Therefore, a fully 3D non-hydrostatic model (FLOW 3D) was used in this paper to simulate the wave generation, propagation and overtopping.

**GC-3:** Move the following from 3rd (Methodology) Section to Introduction. P.11, line 10 – P.13, line 17 - contains concrete review of erosion simulation approaches

**Response to GC-3:** We appreciate the suggestion and we have implemented it by moving the text to the Introduction and merging it with the existing text there.

Revised text in Section 1.2:

“Dynamic modeling of moraine erosion and breaching deals with tradeoffs between reliability, complexity, field data demand, and computational power. Several physical processes converge when natural or artificial dams fail; hydrodynamic, erosive, and sediment transport phenomena, as well as movement of boulders and mechanical or slope failures interact during dam collapses (Westoby et al., 2014a; Worni et al., 2014). Modeling the erosion of natural and artificial dams has been evolving since the early 1980’s, when simple one-dimensional models based on empirical and parametric analyses were developed to represent dam-breach processes, e.g., DAMBRK (Fread, 1988), WinDAM B (Visser et al., 2011) and HR-BREACH (Hassan and Morris, 2012; Westoby et al., 2015). These models describe breach phenomena by defining the rate of growth of a potential breach, and including that breach definition in a hydrodynamic model (Rivas et al., 2015; Fread, 1984). These models are computationally efficient but rely

heavily on engineering judgment and analysis of historical failure cases; when the expected breach shape, size and growth rate are unknown, the models have limited ability to predict if sufficient erosion will occur to produce a breach at a particular site.

Many two-dimensional sediment transport models apply a SWE scheme, in which mobile bed meshes respond to shear stresses from hydrodynamic forces, and use empirical functions of non-cohesive sediment transport to estimate drifting, entrainment, suspended transport, bed load transport, and deposition of sediment, e.g., IBER (Bladé et al., 2014), Delft3D (operated as a 2D model) (Deltares, 2014) and BASEMENT (Vetsch et al., 2014). These models have the potential to simulate the moraine erosion process considered here but only BASEMENT is able to account for the important process of slope collapse as erosion occurs and meshes change.

Overtopping waves can cause terminal moraine erosion. Under wave transport conditions, vertical accelerations play an important role in both water and sediment advection, influencing the erosion process and possible moraine failure. Three-dimensional models can efficiently simulate flow phenomena when those vertical accelerations are relevant. However, coupled erosion simulations requiring additional hydro-morphodynamic functions pose additional challenges in three-dimensional modeling. Several models combine three-dimensional numerical schemes with sediment transport formulations, e.g., Delft3D (Deltares, 2014), FLOW3D (Flow Science, 2014) and OpenFoam (Greenshields, 2015). FLOW3D and OpenFoam use a VoF (Volume of Fluid) method to describe the solid-fluid interface, representing sediment beds as an additional fluid in multi-phase schemes. This approach seems successful for applications where the erodible bed remains submerged throughout the entire simulation or under steady flow conditions, but stability problems arise for cells exposed to drying and wetting periods. Delft 3D avoids these stability issues by using a flexible mesh instead of a multi-phase approach to simulate changes due to erosion or deposition; however, it has limitations in representing fluid regions disconnected from boundaries.

Wave overtopping and breach analysis in this paper evolves from the methods reported by Rivas et al. (2015), whose performance evaluation of empirical breach models focused exclusively on hydraulic considerations. That partial perspective sets no physical limit on breach growth, assuming full moraine collapse is possible. This paper goes beyond the previous work to determine the likelihood and potential magnitude of a moraine breach through hydro-morphodynamic simulations of the erosion process. BASEMENT is used to model the dynamic moraine erosion resulting from an overtopping wave. Under this approach, the analysis follows a similar procedure to that applied by Worni et al. (2012, 2014) at Lake Ventisquero Negro, but it reduces the limitations on modeling waves that can cause further moraine collapse by using external results from FLOW3D to calibrate the BASEMENT model. This has allowed exploration of the possibility of full, partial or even null breaches at Lake Palcacocha according to flow characteristics while accounting for soil and morphological properties as well.”

Revised text in Section 2 (Study Area):

“Previous attempts at predicting outflow from potential failures of the Lake Palcacocha moraine have assumed, from a worst-case approach, that total or partial collapse of the moraine is possible (Somos-Valenzuela et al., 2014; Rivas et al., 2015). Although the history of GLOFs presents cases of large-scale breaches in diverse glacial settings, whether a total collapse at Lake Palcacocha is physically possible remains an unanswered question. To drain most of its impounded water, Lake Palcacocha requires a breach 985 m wide and 66 m deep, forming a continuous outlet at the front moraine (Rivas et al., 2015). Similar conditions resulted in moraine failure and subsequent outburst floods at Queen Bess Lake (Clague and Evans, 2000), Lake Ventisquero Negro (Worni et al., 2012), or Tam Pokhari Lake (Osti and Egashira, 2009). However, the morphology of Lake Palcacocha possesses a set of unique characteristics that could inhibit a large breach of its present moraine: (1) a reshaped morphology produced by the previous 1941 GLOF event and continuing glacier retreat, with a resulting irregular lake bed as an obstacle to flow; (2) a well-defined and curved outlet channel; and (3) a terminal moraine that resembles a long crested dam with an average width-to-height ratio of 14.9 (Rivas et al., 2015). Huggel et al. (2002, 2004) note that glacial lake damming-moraines with large width–height ratios ( $> 1.0$ ) are much less vulnerable to overtopping and erosion by excess overflow or displacement waves.”

Added text in Section 6 (Conclusions):

“Although no sources of calibration exists for a breach event under the current conditions of Lake Palcacocha, the results showed no sensitivity to drastic variations and assumptions regarding the composition of the soil matrix. A governing assumption on the weakest possible soil composition led to no collapse and only partial damage during wave events. This approach worked well due to the characteristics of the moraine-lake system at Lake Palcacocha (mainly its moraine morphology). However, different conditions at other glacial lakes might require richer calibration and sensitivity considerations, demanding caution for applying this method to different cases.”

**GC-4:** Move the following from 3rd (Methodology) Section to Introduction. P.15, line 10 – P.15, line 27 - provides review of the inundation simulation methods, etc.

**Response to GC-4:** We appreciate the suggestion and we have implemented it by moving the text to the Introduction and merging it with the existing text there.

Revised text in Section 1.2:

“The resulting lake outburst floods, after breaching or overtopping of the moraine, comprise highly unsteady flows that are characterized by pronounced changes as they propagate downstream (Worni et al., 2012). Calculating downstream inundation caused by a GLOF event requires the simulation of debris flow propagation, since sediment entrainment can cause the volume and peak discharge to increase by as much as three times (Worni et al., 2014; Osti and

Egashira, 2009). One-dimensional models based on the St. Venant equations have been used to model the downstream flood wave propagation of a GLOF, e.g., Klimes et al. (2013) who used HEC-RAS (USACE, 2010) to reproduce the 2010 GLOF from Lake 513 in Peru; Cenderelli and Wohl (2003) who used HEC-RAS to reproduce steady-state aspects of GLOFs in the Khumbu region of Nepal; Byers et al. (2013) who used HEC-RAS to model a potential GLOF from Lake 464 in the Hongu valley of Nepal; Meon and Schwarz, (1993) who used DAMBRK (Fread, 1988) to model a potential GLOF in the Arun valley of Nepal; and Bajracharya et al. (2007) who used FLDWAV (NWS, 1998) to model a potential GLOF from Imja Lake in Nepal. Two-dimensional SWE models are often used to model downstream impacts of GLOFs, e.g., Worni et al. (2012) who used BASEMENT to model flooding from a GLOF at Shako Cho Lake in India; Schneider et al. (2014) who used RAMMS to model debris flow from an overtopping wave at Lake 513 in Peru; Somos-Valenzuela et al. (2015) who used FLO2D to model downstream inundation from a potential GLOF at Imja Lake in Nepal; and Mergili et al. (2011) used RAMMS and FLO2D to simulate flooding from Lake Khavraz in Tajikistan. FLO2D (FLO2D, 2012) is used here to simulate the downstream inundation.”

### **Specific Comments:**

**SC-1:** In Fig. 11, I have not found areas of different colors, which are related to the aerial images. Please clarify.

**Response to SC-1:** Thank you for pointing this out. The three RGB channels of the image shown in the legend of the figure have been removed since they are not needed in the figure.

1 **Modeling Glacial Lake Outburst Flood Process Chain: The**  
2 **Case of Lake Palcacocha and Huaraz, Peru**

3  
4 **M. A. Somos-Valenzuela<sup>2</sup>, R. E. Chisolm<sup>1</sup>, D. S. Rivas<sup>1</sup>, C. Portocarrero<sup>3</sup> and D. C.**  
5 **McKinney<sup>1</sup>**

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7 [2] {Department of Civil and Environmental Engineering, University of Massachusetts, Amherst}

8 [3] {Instituto Nacional de Investigación en Glaciares y Ecosistemas de Montaña (INAIGEM),  
9 Huaraz, Peru}

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11  
12 **Abstract**

13 One of the consequences of recent glacier recession in the Cordillera Blanca, Peru, is the risk of  
14 Glacial Lake Outburst Floods (GLOFs) from lakes that have formed at the base of retreating  
15 glaciers. GLOFs are often triggered by avalanches falling into glacial lakes, initiating a chain of  
16 processes that may culminate in significant inundation and destruction downstream. This paper  
17 presents simulations of all of the processes involved in a potential GLOF originating from Lake  
18 Palcacocha, the source of a previously catastrophic GLOF on December 13, 1941, killing about  
19 1800 people in the city of Huaraz, Peru. The chain of processes simulated here includes: (1)  
20 avalanches above the lake; (2) lake dynamics resulting from the avalanche impact, including wave  
21 generation, propagation, and run-up across lakes; (3) terminal moraine overtopping and dynamic  
22 moraine erosion simulations to determine the possibility of breaching; (4) flood propagation along  
23 downstream valleys; and (5) inundation of populated areas. The results of each process feed into  
24 simulations of subsequent processes in the chain, finally resulting in estimates of inundation in the  
25 city of Huaraz. The results of the inundation simulations were converted into flood intensity and  
26 preliminary hazard maps (based on an intensity-likelihood matrix) that may be useful for city  
27 planning and regulation. Three avalanche events with volumes ranging from  $0.5\text{-}3 \times 10^6 \text{ m}^3$  were  
28 simulated, and two scenarios of 15 m and 30 m lake lowering were simulated to assess the potential

1 of mitigating the hazard level in Huaraz. For all three avalanche events, three-dimensional  
2 hydrodynamic models show large waves generated in the lake from the impact resulting in  
3 overtopping of the damming-moraine. Despite very high discharge rates (up to  $63.4 \times 10^3 \text{ m}^3 \text{ s}^{-1}$ ),  
4 the erosion from the overtopping wave did not result in failure of the damming-moraine when  
5 simulated with a hydro-morphodynamic model using excessively conservative soil characteristics  
6 that provide very little erosion resistance. With the current lake level, all three avalanche events  
7 result in inundation in Huaraz due to wave overtopping, and the resulting preliminary hazard map  
8 shows a total affected area of  $2.01 \text{ km}^2$ , most of which is in the high-hazard category. Lowering  
9 the lake has the potential to reduce the affected area by up to 35% resulting in a smaller portion of  
10 the inundated area in the high-hazard category.

## 11 12 **1 Introduction**

### 13 **1.1 Climate impacts in the Cordillera Blanca of Peru**

14 Atmospheric warming has induced melting of many glaciers around the world (WGMS, 2012;  
15 IPCC, 2013; Marzeion et al., 2014). The formation of new lakes in de-glaciating high-mountain  
16 regions strongly influences landscape characteristics and represents a significant hazard related to  
17 climate change (Frey et al., 2010; Rosenzweig et al., 2007; Kattelman, 2003; Richardson and  
18 Reynolds, 2000). The glacier-covered area of the Cordillera Blanca range in Peru has decreased  
19 from a Little Ice Age peak of  $900 \text{ km}^2$  to about  $700 \text{ km}^2$  in 1970,  $528 \text{ km}^2$  in 2003, and further  
20 decreased to  $482 \text{ km}^2$  in 2010 (UGRH, 2010; Burns and Nolin, 2014). As a consequence of this  
21 glacier recession, many glacial lakes have formed or expanded in the Cordillera Blanca that pose  
22 various levels of Glacial Lake Outburst Flood (GLOF) risk for communities below these lakes  
23 (Emmer and Vilimek, 2013).

24 The steep summits of the Cordillera Blanca are undergoing long-term slope destabilization due to  
25 warming and permafrost degradation (Haeberli, 2013). Related ice and rock avalanches are  
26 especially dangerous in connection with glacial lakes forming or expanding at the foot of steep  
27 mountain slopes because they can trigger large waves in the lakes and potentially lead to GLOFs  
28 (Carey et al., 2012; Haeberli, 2013). There are many examples in the Cordillera Blanca of glacier-  
29 related incidents and catastrophes (Lliboutry et al., 1977; Carey, 2010; Portocarrero, 2014). A

1 recent example in the Cordillera Blanca is the 2010 event comprised of a nearly 0.5 million m<sup>3</sup>  
2 ice/rock avalanche from the summit of Nevado Hualcán that fell into Lake 513 and generated  
3 waves that overtopped the natural rock dam of the lake, producing flood waves and debris flows  
4 that reached the town of Carhuaz (Carey et al., 2012; Schneider et al., 2014). Preventive lowering  
5 of Lake 513 by artificial tunnels in the 1990s, creating a freeboard of 20 meters, helped avoid a  
6 major catastrophe that could have killed many people (Reynolds et al., 1998; Carey et al., 2012;  
7 Portocarrero, 2014).

## 8 **1.2 Introduction to glacial lake hazard process chain modeling**

9 Emmer and Vilímek (2013, 2014) and Haeberli et al. (2010) have recommended that the evaluation  
10 of glacial lake hazards be based on systematic and scientific analysis of lake types, moraine dam  
11 characteristics, outburst mechanisms, down-valley processes and possible cascades of processes.  
12 Changes in climate patterns are likely to increase the frequency of avalanches as a consequence of  
13 reduced stability of permafrost, bedrock and steep glaciers in the Cordillera Blanca (Fischer et al.,  
14 2012). Under these conditions, avalanches are the most likely potential trigger of GLOFs (Emmer  
15 and Vilímek, 2013; Emmer and Cochachin, 2013; Awal et al., 2010; Bajracharya et al., 2007;  
16 Richardson and Reynolds, 2000; Costa and Schuster, 1988), acting as the first link in a chain of  
17 dependent processes propagating downstream: (1) large avalanche masses reaching nearby lakes,  
18 (2) wave generation, propagation, and runup across lakes, (3) terminal moraine overtopping and/or  
19 moraine breaching, (4) flood propagation along downstream valleys; and (5) inundation of riverine  
20 populated areas (Worni et al., 2014; Westoby et al., 2014b).

21 Few studies have attempted to simulate an entire GLOF hazard process chain in a single modeling  
22 environment, generally limiting the number of processes considered; e.g., Worni et al. (2014)  
23 excluded avalanche simulations from their modeling framework. Worni et al. (2014) and Westoby  
24 et al. (2014a) review typical modeling approaches for GLOFs that involve land or ice masses  
25 falling into glacial lakes. An approach that separately simulates individual processes predominates,  
26 where different processes are connected by using the results of one model as the input for the  
27 simulation of the next (e.g., Schneider et al., 2014; Westoby et al., 2014b, Worni et al., 2014). In  
28 this paper, this approach was used to produce simulations of each process in the chain from  
29 avalanche to inundation, ensuring that the processes were properly depicted. The glacial lake  
30 hazard process chain simulated here includes: avalanche movement into a lake, wave generation



1 and lake hydrodynamics, wave overtopping and moraine erosion, and downstream sediment  
2 transport and inundation.

3 **Physical** models of avalanche phenomena have been used to simulate mass movement processes,  
4 e.g., snow avalanches, rock slides, rock avalanches or debris flows (Schneider et al., 2010). Rock-  
5 ice avalanches exhibit flow characteristics similar to all of these processes, and the choice of an  
6 appropriate model is difficult because available models are not able to fully simulate all of the  
7 elements of these complex events. Schneider et al. (2010) tested the Rapid Mass Movements  
8 RAMMS model (Bartelt et al., 2013), a two-dimensional dynamic physical model based on the  
9 shallow water equations (SWE) for granular flows and the Voellmy frictional rheology to  
10 successfully reproduce the flow and deposition geometry as well as dynamic aspects of large rock-  
11 ice avalanches. RAMMS was used here to determine the characteristics of various size avalanches  
12 entering the lake, one of the more difficult elements in modeling the process chain.

13 **Impulse** waves resulting from the impact of an avalanche with the lake were simulated with a  
14 three-dimensional hydrodynamic model, FLOW3D (Flow Science, 2012). Much of the work in  
15 impulse wave generation, propagation and run-up has been focused on empirical models that  
16 replicate wave characteristics based on laboratory observations (Kamphuis and Bowering 1970;  
17 Slingerland and Voight, 1979, 1982; Fritz et al., 2004; Heller and Hager, 2010); numerical  
18 simulations have been limited to simplified two-dimensional SWE simulations (Rzadkiewicz et  
19 al., 1997; Biscarini, 2010; Cremonesi et al., 2011; Ghozlani et al., 2013; Zweifel et al., 2006).  
20 However, the 2D SWE representations do a poor job of modeling wave generation and propagation  
21 because vertical accelerations are important and cannot be neglected for slide-generated waves  
22 (Heinrich, 1992; Zweifel et al., 2006). Analytical calculations of wave run-up and overtopping  
23 typically consider simplified lake geometries (e.g., uniform water depth and constant slope of the  
24 terminal moraine) that do not necessarily hold true in natural reservoirs (Synolakis, 1987, 1991;  
25 Muller, 1995; Liu et al., 2005). The limitations of empirical and 2D SWE models for simulating  
26 lake dynamics leave an opening for a more robust approach. Therefore, a fully 3D non-hydrostatic  
27 model (FLOW 3D) was used in this paper to simulate the wave generation, propagation and  
28 overtopping.

29 Dynamic modeling of **moraine erosion** and **breaching** deals with tradeoffs between reliability,  
30 complexity, field data demand, and computational power. Several physical processes converge

**Comment [DCM1]:** GC-1: not all mentioned references are explicitly related to the methodology used in the study. It is not clear which achievements of the previous models and methods are utilized, which drawbacks need to be improved in this study and so on.

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**Deleted:** ; Christen et al., 2010

**Comment [DCM3]:** GC-2: Moved from Methodology to Introduction – Wave simulation

**Deleted:** Empirical models have been developed that analytically calculate wave characteristics (Heller and Hager, 2010), and some hydrodynamic simulations have been performed for this type of problem (Worni et al., 2012; Schneider et al., 2014). Most hydrodynamic simulations of avalanche-generated waves use two-dimensional models employing the shallow water equations despite the relative importance of vertical accelerations that cannot be considered in 2D shallow water schemes (Heinrich, 1992; Zweifel et al., 2006). Fully 3D, non-hydrostatic models, e.g., FLOW3D (Flow Science, 2012), can simulate the important characteristics of the wave-generation, propagation and overtopping of a terminal moraine in an avalanche-triggered GLOF and take into account irregular lake bathymetries and geometries.

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**Comment [DCM4]:** GC-3: Moved text from Methodology to Introduction – Erosion simulation

1 when natural or artificial dams fail; hydrodynamic, erosive, and sediment transport phenomena, as  
2 well as movement of boulders and mechanical or slope failures interact during dam collapses  
3 (Westoby et al., 2014a; Worni et al., 2014). Modeling the erosion of natural and artificial dams  
4 has been evolving since the early 1980's, when simple one-dimensional models based on empirical  
5 and parametric analyses were developed to represent dam-breach processes, e.g., DAMBRK  
6 (Fread, 1988), WinDAM B (Visser et al., 2011) and HR-BREACH (Hassan and Morris, 2012;  
7 Westoby et al., 2015). These models describe breach phenomena by defining the rate of growth of  
8 a potential breach, and including that breach definition in a hydrodynamic model (Rivas et al.,  
9 2015; Fread, 1984). These models are computationally efficient but rely heavily on engineering  
10 judgment and analysis of historical failure cases; when the expected breach shape, size and growth  
11 rate are unknown, the models have limited ability to predict if sufficient erosion will occur to  
12 produce a breach at a particular site.

13 Many two-dimensional sediment transport models apply a SWE scheme, in which mobile bed  
14 meshes respond to shear stresses from hydrodynamic forces, and use empirical functions of non-  
15 cohesive sediment transport to estimate drifting, entrainment, suspended transport, bed load  
16 transport, and deposition of sediment, e.g., IBER (Bladé et al., 2014), Delft3D (operated as a 2D  
17 model) (Deltares, 2014) and BASEMENT (Vetsch et al., 2014). These models have the potential  
18 to simulate the moraine erosion process considered here but only BASEMENT is able to account  
19 for the important process of slope collapse as erosion occurs and meshes change.

20 Overtopping waves can cause terminal moraine erosion. Under wave transport conditions, vertical  
21 accelerations play an important role in both water and sediment advection, influencing the erosion  
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26 sediment transport formulations, e.g., Delft3D (Deltares, 2014), FLOW3D (Flow Science, 2014)  
27 and OpenFoam (Green Shields, 2015). FLOW3D and OpenFoam use a VoF (Volume of Fluid)  
28 method to describe the solid-fluid interface, representing sediment beds as an additional fluid in  
29 multi-phase schemes. This approach seems successful for applications where the erodible bed  
30 remains submerged throughout the entire simulation or under steady flow conditions, but stability  
31 problems arise for cells exposed to drying and wetting periods. Delft 3D avoids these stability

**Deleted:** The combined behavior of these processes, under heterogeneous natural conditions, makes it challenging to predict how a breach might develop, and whether a complete collapse may occur in natural dams (Wahl, 2010; Walder and O'Connor, 1997), leading to modeling simplifications when trying to simulate such phenomena.

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1 issues by using a flexible mesh instead of a multi-phase approach to simulate changes due to  
2 erosion or deposition; however, it has limitations in representing fluid regions disconnected from  
3 boundaries.

4 Wave overtopping and breach analysis in this paper evolves from the methods reported by Rivas  
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8 the likelihood and potential magnitude of a moraine breach through hydro-morphodynamic  
9 simulations of the erosion process. BASEMENT is used to model the dynamic moraine erosion  
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11 to that applied by Worni et al. (2012, 2014) at Lake Ventisquero Negro, but it reduces the  
12 limitations on modeling waves that can cause further moraine collapse by using external results  
13 from FLOW3D to calibrate the BASEMENT model. This has allowed exploration of the  
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15 characteristics while accounting for soil and morphological properties as well.

16 The resulting lake outburst floods, after breaching or overtopping of the moraine, comprise highly  
17 unsteady flows that are characterized by pronounced changes as they propagate downstream  
18 (Worni et al., 2012). Calculating downstream inundation caused by a GLOF event requires the  
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20 discharge to increase by as much as three times (Worni et al., 2014; Osti and Egashira, 2009). One-  
21 dimensional models based on the St. Venant equations have been used to model the downstream  
22 flood wave propagation of a GLOF, e.g., Klimes et al. (2013) who used HEC-RAS (USACE, 2010)  
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24 RAS to reproduce steady-state aspects of GLOFs in the Khumbu region of Nepal; Byers et al.  
25 (2013) who used HEC-RAS to model a potential GLOF from Lake 464 in the Hongu valley of  
26 Nepal; Meon and Schwarz, (1993) who used DAMBRK (Fread, 1988) to model a potential GLOF  
27 in the Arun valley of Nepal; and Bajracharya et al. (2007) who used FLDWAV (NWS, 1998) to  
28 model a potential GLOF from Imja Lake in Nepal. Two-dimensional SWE models are often used  
29 to model downstream impacts of GLOFs, e.g., Worni et al. (2012) who used BASEMENT to  
30 model flooding from a GLOF at Shako Cho Lake in India; Schneider et al. (2014) who used  
31 RAMMS to model debris flow from an overtopping wave at Lake 513 in Peru; Somos-Valenzuela

**Deleted:** (e.g., Lake Palcacocha at the center of the simulation domain, with no initial connection to the outlet downstream boundary and intermittent wetting and drying periods across the domain)

**Deleted:** Worni et al. (2012) used BASEMENT to reproduce historic overtopping driven failures in Lake Ventisquero Negro. Despite the limitations of the BASEMENT two-dimensional SWE scheme, results show good agreement with the limited field data available, at least in terms of final breach dimensions.

**Deleted:** adapting

**Comment [DCM5]:** GC-4: Moved text from Methodology to Introduction – Inundation simulation

**Deleted:** Various 2D flow models have been used to simulate the downstream inundation caused by a GLOF, including BASEMENT (Worni et al., 2012), which includes sediment transport functions but no capabilities for debris flow simulation; FLO2D (Mergili et al., 2011; Somos-Valenzuela et al., 2015) and RAMMS (Schneider et al., 2014), otherwise, do account for debris flow.

**Deleted:** . These models typically use the step-backwater procedure, and cross-sectional averaged velocity and discharge (Westoby et al., 2014a). Examples of this type of model include

**Deleted:** based on the depth-averaged SWE

**Deleted:** (Westoby et al., 2014a). Examples of applying this type of model include

**Deleted:** propagation

**Deleted:** from the 2010 GLOF event

1 et al. (2015) who used FLO2D to model downstream inundation from a potential GLOF at Imja  
2 Lake in Nepal; and Mergili et al. (2011) used RAMMS and FLO2D to simulate flooding from  
3 Lake Khavraz in Tajikistan. FLO2D (FLO2D, 2012) is used here to simulate the downstream  
4 inundation.

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Deleted: and hyper-concentrated flows

5 As an interpretation of downstream consequences, flood hazard denotes potential levels of threat  
6 as a function of intensity and likelihood of the arriving inundation (normally probability, but the  
7 nature of avalanche events and other processes in the hazard chain restricts from assigning  
8 numerical probabilities). Flood intensity is determined by the flow depth and velocity (García et  
9 al., 2003; Servicio Nacional de Geología y Minería, 2007). Likelihood is inversely related to  
10 magnitude, i.e., large events are less likely to occur (low frequency) than small events (Huggel et  
11 al., 2004). Maps can be prepared that show the level of hazard resulting from the intensity of  
12 various likelihood events. This allows communication of the flood hazard at various locations,  
13 facilitating planning, regulation, and zoning based on the map while enhancing communication to  
14 the affected community (O'Brien, 2012; USBR, 1988; FEMA, 2003).

15 This paper describes an analysis of the processes involved in a potential GLOF from Lake  
16 Palcacocha in Peru and the resulting inundation downstream in the city of Huaraz. The simulated  
17 process cascade starts from an avalanche falling into the lake, resulting in a wave that overtops the  
18 damming-moraine; the simulation continues with potential erosion due to moraine overtopping  
19 and culminates with simulations of the ensuing downstream flooding and inundation in Huaraz. In  
20 the following sections, the setting of the problem is presented, followed by descriptions of the  
21 physical basis and modeling of each of the processes in the chain. The results of each of the  
22 simulated processes are presented, concluding with details of the potential inundation in Huaraz  
23 and hazard implications. Mitigation alternatives are investigated through an analysis of several  
24 lake-lowering scenarios.

## 25 **2 Study Area**

26 Lake Palcacocha is located at 9°23' S, 77°22' W at an elevation of 4,562 m in the Department of  
27 Ancash in Peru (Figure 1) and is part of the Quillcay watershed in the Cordillera Blanca. The outlet  
28 of the lake flows into the Paria River, a tributary of the Quillcay River that passes through the city  
29 of Huaraz. The Quillcay drains into the Santa River, the primary river of the region. The lake had

1 a maximum depth of 72 m in 2009 and an average water surface elevation of 4562 m (UGRH,  
2 2009).

3 The danger of a GLOF from Lake Palcacocha is paramount (HiMAP, 2014). A GLOF originating from the  
4 lake occurred in 1941, flooding the downstream city of Huaraz, killing about 1800 people (according to  
5 best estimates) (Wegner, 2014) and destroying infrastructure and agricultural land all the way to the coast  
6 (Carey, 2010; Evans et al., 2009). The Waraq Commonwealth, a government body established by the  
7 local municipalities of Huaraz and Independencia, was created to implement adaptation projects  
8 related to climate change on water resources; at present, the Commonwealth is planning a GLOF  
9 early warning system for Lake Palcacocha.

10 Prior to the 1941 GLOF, the lake had an estimated volume of 10 to 12 million m<sup>3</sup> of water (Instituto  
11 Nacional de Defensa Civil, 2011). After the 1941 GLOF, the volume was reduced to about 500,000  
12 m<sup>3</sup> (Portocarrero, 2014). Lowering the level of glacial lakes is a common GLOF mitigation  
13 practice in the Cordillera Blanca (Portocarrero, 2014). In 1974, drainage structures were built at  
14 the lake to maintain 8 m of freeboard at the lake outlet, a level that at the time was thought to be  
15 safe from additional avalanche generated waves. Nineteen years later, in March 2003, a landslide  
16 from the lateral moraine along the lake's southern side entered the lake, launching a diagonal wave  
17 that traversed the lake and heavily eroded the reinforced dam. There was a small outflow from the  
18 lake, but no serious damage occurred in Huaraz; however, the event frightened the Huaraz city  
19 authorities. The regional government quickly repaired the damaged structures (Portocarrero,  
20 2014).

21 Lake Palcacocha continues to pose a threat, since in recent years it has grown to the point where  
22 its volume is over 17.3 million m<sup>3</sup> (UGRH 2009). As shown in Rivas et al. (2015, Fig. 4), the area  
23 of the lake has grown continuously from 0.16 km<sup>2</sup> in 2000 to 0.48 km<sup>2</sup> in 2012. Avalanches from  
24 the steep surrounding slopes can reach the lake directly and potentially generate waves that could  
25 overtop and possibly erode the moraine dam, thus triggering a GLOF that could reach Huaraz  
26 (Hegglin and Huggel, 2008; Instituto Nacional de Defensa Civil, 2011). In 2010, Lake Palcacocha  
27 was declared to be in a state of emergency because its increasing water level was deemed unsafe  
28 (Diario la Republica, 2010; Instituto Nacional de Defensa Civil, 2011). Infrastructures at risk are  
29 spread between the lake and the city, including small houses, a primary school, fish farms, and  
30 water supply facilities. Siphons were installed in 2011 at the lake to temporarily lower the water  
31 surface of the lake by 3-5 m providing a total free board of about 12 m; however, further lowering

1 of the lake to provide additional freeboard has been recommended (Portocarrero, 2014). Given the  
2 complexity of the problem and lack of information, local authorities and residents of Huaraz are  
3 concerned about the threat posed by the lake and have requested technical support to investigate  
4 the impacts that a GLOF could have on Huaraz and methods to reduce the risk. The latest hazard  
5 assessment for Lake Palcacocha (Emmer and Vilimek, 2014) has concluded that a GLOF resulting  
6 from moraine overtopping following an avalanche into the lake is likely; however, complete  
7 moraine failure resulting from an avalanche-generated wave is not likely, nor is moraine failure  
8 following a strong earthquake.

9 Previous attempts at predicting outflow from potential failures of the Lake Palcacocha moraine  
10 have assumed, from a worst-case approach, that total or partial collapse of the moraine is possible  
11 (Somos-Valenzuela et al., 2014; Rivas et al., 2015). Although the history of GLOFs presents cases  
12 of large-scale breaches in diverse glacial settings, whether a total collapse at Lake Palcacocha is  
13 physically possible remains an unanswered question. To drain most of its impounded water, Lake  
14 Palcacocha requires a breach 985 m wide and 66 m deep, forming a continuous outlet at the front  
15 moraine (Rivas et al., 2015). Similar conditions resulted in moraine failure and subsequent outburst  
16 floods at Queen Bess Lake (Clague and Evans, 2000), Lake Ventisquero Negro (Worni et al.,  
17 2012), or Tam Pokhari Lake (Osti and Egashira, 2009). However, the morphology of Lake  
18 Palcacocha possesses a set of unique characteristics that could inhibit a large breach of its present  
19 moraine: (1) a reshaped morphology produced by the previous 1941 GLOF event and continuing  
20 glacier retreat, with a resulting irregular lake bed as an obstacle to flow; (2) a well-defined and  
21 curved outlet channel; and (3) a terminal moraine that resembles a long crested dam with an  
22 average width-to-height ratio of 14.9 (Rivas et al., 2015). Huggel et al. (2002, 2004) note that  
23 glacial lake damming-moraines with large width–height ratios (> 1.0) are much less vulnerable to  
24 overtopping and erosion by excess overflow or displacement waves.

25 A recent 5 m x 5 m horizontal resolution Digital Elevation Model (DEM) of the Quillcay watershed  
26 generated by airborne LIDAR and new stereo aerial photographs was developed for this work by  
27 the Peruvian Ministry of Environment (Horizons, 2013) (Figure 1). Bathymetric data from a 2009  
28 survey (UGRH, 2009) were combined with the surrounding DEM for the lake hydrodynamic and  
29 dynamic breach simulations.

**Comment [DCM6]:** GC-3: Moved from Methodology to Introduction – Erosion simulation

## 1 **3 Methodology**

### 2 **3.1 Overview**

3 The methodology presented here considers a process chain similar to Worni et al. (2014) depicting  
4 an avalanche triggered GLOF from Lake Palcacocha to assess the potential inundation in Huaraz  
5 from such an event (Figure 2). The simulated avalanche originates from the Palcaraju glacier  
6 located directly above the lake. When an avalanche enters the lake, depending on its size and the  
7 level of the water surface in the lake, the resulting wave might overtop the damming-moraine and  
8 possibly initiate an erosive breaching process releasing considerable amounts of water and debris  
9 into the Paria River and potentially inundating densely populated areas of Huaraz downstream.  
10 The process chain from avalanche to inundation was simulated using four models: potential  
11 avalanches were modeled using RAMMS (Christen et al., 2010), lake wave dynamics were  
12 modeled with FLOW3D (Flow Science, 2012), the dynamic breaching process was simulated in  
13 BASEMENT (Vetsch et al., 2006), and propagation of the flood wave downstream and inundation  
14 in Huaraz were simulated in FLO2D (O'Brien, 2003).

15 The next sections describe each component for the framework used to simulate the hazard  
16 process chain: avalanche simulation, wave simulation in the lake, moraine erosion simulation,  
17 inundation simulation, and hazard identification.

### 18 **3.2 Avalanche simulation**

19 In non-forested areas, ice-rock avalanches can be generated on slopes of 30-50°, and in tropical  
20 areas the critical slope can be even less (Christen et al., 2005; Haeberli, 2013). Temperate glaciers  
21 can produce ice avalanches if the slope of the glacier bed is 25° or more, but rare cases with slopes  
22 less than 17° have occurred (Alean, 1985). The mountains surrounding Lake Palcacocha have  
23 slopes up to 55°; therefore, they have a high chance of generating avalanche events. Nonetheless,  
24 it is difficult to forecast when avalanches will occur and where the detachment zone will be located  
25 (Evans and Clague, 1988; Haeberli et al., 2010).

26 The Rapid Mass Movements (RAMMS) avalanche model was used to simulate the progression of  
27 avalanches down the mountain to the lake. RAMMS solves two-dimensional, depth-averaged mass  
28 and momentum equations for granular flow on three-dimensional terrain using a finite volume

1 method (Christen et al., 2010; Bartelt et al., 2013). The inputs for the model include: (1) terrain  
2 data (a DEM, described above); (2) fracture height; (3) the avalanche release area; and (4) friction  
3 parameters. Descriptions of input parameters (2) - (4) and the criteria used to determine their values  
4 are given in the following paragraphs. RAMMS computes the velocity of the avalanche, the  
5 distance of the runout, the pressure distribution, and the height of the avalanche front at different  
6 locations below the initiation point.

7 For the elevation of the Palcaraju glacier above Lake Palcacocha, the potential fracture type is  
8 expected to be a slab failure or type I fracture as defined by Alean (1985). Huggel et al. (2004),  
9 after Alean (1985), suggest that ice avalanches in slab failures are mainly produced in small and  
10 steep glaciers with thicknesses between 30 to 60 m, where they are less frequent in large valley-  
11 type glaciers. Alean (1985) shows examples of slab failure with thicknesses ranging from 19 to 35  
12 m and volumes ranging from 1 to 11 million m<sup>3</sup>. The avalanche above Lake 513 that occurred in  
13 2010 is an example of this type of failure (Schneider et al., 2014). Following these precedents,  
14 fracture heights of 25 m, 35 m and 45 m were selected for simulating the small, medium and large  
15 avalanches respectively.

16 Three avalanche volumes are considered in this work, similar to the avalanche scenarios in  
17 Schneider et al. (2014): 0.5x10<sup>6</sup> m<sup>3</sup> (small), 1x10<sup>6</sup> m<sup>3</sup> (medium) and 3x10<sup>6</sup> m<sup>3</sup> (large). These  
18 potential avalanche volumes are consistent with the elevations and slopes of the source area. The  
19 release area (shown in Figure 3) was located at an elevation of 5200 m to the north east of the lake  
20 following the main axis of the lake.

21 The friction parameters required by the RAMMS model are (1) the density of the rock and ice ( $\rho$ ,  
22 in kg m<sup>-3</sup>), (2) the Coulomb-friction term ( $\mu$ ), and (3) the turbulent friction parameter ( $\xi$ ) (Bartelt  
23 et al., 2013). The Coulomb-friction term with a dry surface friction dominates the total friction  
24 when the flow is relatively slow, and the turbulent friction parameter tends to dominate when the  
25 flow is rapid, as is the case with the avalanches considered here (Bartelt et al., 2013; Christen et  
26 al., 2010, 2008). The friction parameter values used in the RAMMS avalanche model are:  
27  $\xi=1000\text{ms}^{-2}$ ,  $\mu = 0.12$  and  $\rho = 1000\text{ kg m}^{-3}$ , values similar to those used to model the avalanche  
28 into Lake 513 (Schneider et al., 2014).



### 1 3.3 Lake simulation

2 Lake Palcacocha is very deep near the glacier with depths up to 72 m, but the last several hundred  
3 meters adjacent to the terminal moraine are very shallow with depths mostly less than 10 m (Figure  
4 4). This discontinuous lakebed geometry significantly affects wave propagation and runup, making  
5 a hydrodynamic simulation necessary to represent the potential overtopping of the terminal  
6 moraine.

7 To overcome the limitations of analytical methods such as Heller and Hager (2010) in representing  
8 wave propagation, run-up and overtopping of the moraine, the three-dimensional hydrodynamic  
9 model FLOW3D (Flow Science 2012) was used to simulate the dynamics of avalanche-generated  
10 waves in Lake Palcacocha. The FLOW3D model grid used 400, 150, and 100 grid cells covering  
11 distances of 2400 m, 800 m, and 650 m in the x, y, and z directions, respectively. The RNG  
12 turbulence model with a dynamically computed mixing length and a fully three-dimensional, non-  
13 hydrostatic numerical scheme was used in the FLOW3D simulations.

14 The transfer of mass and momentum from the avalanche to the lake upon impact and the  
15 subsequent wave generation and propagation were simulated in FLOW3D by representing the  
16 avalanche as a volume of water equivalent to the avalanche volume that flows into the lake from  
17 the terrain above. Worni et al. (2014) and Fah (2005) approach the problem in the same way,  
18 simulating water instead of avalanche material. The density of the mixture of snow, rock and ice  
19 present in an avalanche is very close to the density of water (Schneider et al., 2014). Although the  
20 viscosities of the two fluids are different, this approximation of substituting water for the avalanche  
21 fluid is handled through adjustments in the model that compensate for any reduction in dissipation  
22 of energy due to the lower viscosity of water. To accomplish this, the results of the RAMMS  
23 avalanche model were used as calibration parameters; the depth of the avalanche fluid volume and  
24 height above the lake at which it is released were iteratively adjusted in FLOW3D until the  
25 velocities and depths of the avalanche fluid volume entering the lake matched the characteristics  
26 of the avalanche modeled in RAMMS. As long as the mass and momentum of the material hitting  
27 the lake in FLOW3D is similar to that of the RAMMS simulated avalanche, the initial displacement  
28 wave should behave similarly as well; the water in the lake is pushed by the incoming avalanche,  
29 but the avalanche material does not reach the moraine, and the displaced wave is what propagates  
30 across the lake. Differences may arise for reflected waves since the avalanche material might settle

1 in a different way over the lake's bed according to the avalanche properties (water representing  
2 avalanche material is more free to flow in the lake than actual rock-ice avalanche material). The  
3 primary output from the model is a hydrograph of wave overtopping discharge, if there is any, that  
4 is used as input to the downstream inundation model discussed later.

### 5 **3.4 Moraine erosion simulation**

6 In this paper, BASEMENT was used for hydro-morphodynamic simulations of potential erosion-  
7 driven breach-failures at Lake Palcacocha. To overcome the two-dimensional SWE limitations of  
8 BASEMENT, results of three-dimensional hydrodynamic lake and overtopping wave simulations  
9 from FLOW3D were used as calibration parameters. The wave propagation and overtopping of  
10 the terminal moraine were simulated in both FLOW3D and BASEMENT. The zone of interest for  
11 BASEMENT simulations was at the terminal moraine, where erosion can occur and produce a  
12 moraine collapse. However, simulating the wave propagation across the whole lake moves the  
13 upstream boundary of the model, favoring a smoother transition at the interface between both  
14 models, where flow properties must match.

15 The BASEMENT model was started in the zone of the lake where wave generation occurs (wave  
16 splash zone in Figure 5), but the method of simulating wave generation was different from that  
17 used in FLOW3D because the flow characteristics at the inflow boundary must be artificially  
18 altered to compensate for the additional energy loss in the 2D shallow water equation (SWE)  
19 representation of BASEMENT. To facilitate comparison between the FLOW3D and BASEMENT  
20 models, hydrographs of results were compared at a common cross-section for both models, located  
21 at the crest of the terminal moraine (target cross-section in Figure 5). Adjusting the slope of the  
22 energy grade line at the upstream boundary (Figure 5) allowed an iterative increase in momentum  
23 inflow until mass and momentum fluxes over the crest of the moraine (target cross-section)  
24 matched the results from the FLOW3D simulations.

25 The relevant regions of the FLOW3D model, where fluid motion influences erosion and breach-  
26 growth, are located near the moraine crest and downstream in the outlet channel. Through a  
27 calibration procedure, the BASEMENT model was forced to replicate the hydrodynamic  
28 conditions of the FLOW3D wave model. This was achieved by forcing momentum fluxes (that are  
29 dissipated further downstream) at the inflow boundary of the BASEMENT model to be

1 unrealistically high. By adjusting energy slopes at the upstream boundary, momentum inflow was  
2 iteratively increased until flow properties (mass and momentum fluxes) match the results from full  
3 three-dimensional simulations according to hydrographs of discharge and velocity at the crest of  
4 the artificial dam. This procedure aims to guarantee that BASEMENT can properly model mass  
5 transport from wave phenomena despite the limitations of the two-dimensional SWE simulations.

6 BASEMENT applies empirical functions to estimate erosion and deposition rates taking place  
7 under the influence of flows from overtopping waves. Erosion resistance comes from soil  
8 properties and the morphology of the bed. We have applied a hypothetical set of worst-case soil  
9 conditions, intentionally decreasing the erosional strength in the Lake Palcacocha moraine. The  
10 logic of this approach is that if breach simulations show no moraine collapse under the worst  
11 possible conditions observed in the field, such collapse is unlikely to occur in real settings, where  
12 the total soil matrix may contain soil that is more erosion resistant. This approach also seeks to  
13 overcome a lack of independent erosion measurements, which makes any attempt at calibration  
14 and further refinement of the breach model impossible.

15 The bed load transport is modeled with the single-grain Meyer-Peter and Müller (1948) (MPM)  
16 model, which automatically discards any erosion resistance from hiding and armoring processes  
17 occurring in multi-grain matrixes (Ashida and Michiue, 1971; Wu et al., 2000). Correction factors  
18 to account for under- or over-prediction of the rate of bed load transport in the MPM model range  
19 from 0.5 for low transport of sands and gravels to 1.7 for high transport cases (Fernandez and Van  
20 Beek, 1976; Ribberink, 1998; Wong and Parker, 2006). A bed-load factor of 2.0 is used here,  
21 characterizing high sediment transport conditions. Table 1 displays the set of sediment and slope  
22 failure characteristics used to build the Lake Palcacocha hydro-morphodynamic model in  
23 BASEMENT. According to field data, coarser soils ( $d_{50} \approx 19$  mm) predominate at the walls of the  
24 outlet channel left by the 1941 GLOF at Lake Palcacocha (Novotny and Klimes, 2014) where most  
25 of the outburst water would flow in a potential future event. In agreement with the proposed  
26 hypothetical worst-case soil condition, a grain size of  $d_{50} = 1$  mm is assumed, representing  
27 characteristics of upper layer soils that may lead to significant underestimation of erosion  
28 resistance.

### 1 3.5 Inundation simulation

2 FLO2D (FLO2D, 2012) is used to simulate the flooding downstream of Lake Palcacocha  
3 considering debris flow that incorporates sediment characteristics (dynamic viscosity and yield  
4 stress) as exponential functions of the sediment concentration by volume. Although the simulation  
5 grid in FLO2D is two-dimensional, the flow is modeled in eight directions, solving the one-  
6 dimensional continuity and momentum equations in each direction independently using a central,  
7 finite difference method with an explicit time-stepping scheme. One of the advantages of FLO2D  
8 is that for flows with high sediment concentration the total friction slope can be expressed as a  
9 function of the sediment characteristics and the flow depth (FLO2D, 2012; Julien, 2010; O'Brien  
10 et al., 1993).

11 Due to the steepness of the terrain below Lake Palcacocha and low cohesion of the material from  
12 the moraine, high velocities and turbulent flows with low dynamic viscosity and low yield stress  
13 are expected (Julien and Leon, 2000). Therefore, from the empirical coefficients recommended by  
14 FLO2D (2012) these two sets of parameters, that describe low yield stress and dynamic viscosity  
15 respectively, are used:  $\alpha_1 = 0.0765$ ,  $\beta_1 = 16.9$ ,  $\alpha_2 = 0.0648$  and  $\beta_2 = 6.2$ . Yield stress and viscosity  
16 of the flow vary principally with sediment concentration based on empirical relationships where  
17 the parameters  $\alpha_i$  and  $\beta_i$  have been defined by laboratory experiment (FLO2D, 2012).

18 Downstream of Lake Palcacocha the flood will meet huge moraines in a steep canyon. According  
19 to Huggel et al. (2004), erosion on the order of  $750 \text{ m}^3 \text{ m}^{-1}$  has been found in alpine moraines. In  
20 the Andes and Himalaya, erosion cuts can be higher than  $2000 \text{ m}^3 \text{ m}^{-1}$ , with peak flow  
21 concentrations by volume on the order of 60-80%. Thus, given the uncertainties associated to the  
22 calculation of the concentration of sediment, Huggel et al. (2004) recommend using an upper limit  
23 for the average flow concentration by volume of 50-60%. This agrees with Schneider et al. (2014),  
24 Julien and Leon (2000) and Rickenmann (1999) who recommend 50% sediment concentration by  
25 volume, which is used in this study.

26 For the terrain elevation, a DEM was produced for this work (Horizons, 2013). Given the large  
27 extent of the domain, running the inundation simulations on this  $5 \text{ m} \times 5 \text{ m}$  grid was impractical.  
28 Therefore, the FLO2D simulations were run on a  $20 \text{ m} \times 20 \text{ m}$  grid.

29 Distributed roughness coefficient values were assigned based on land cover in the Paria basin  
30 below Lake Palcacocha. Land cover was classified into five categories using the normalized

1 differential vegetation index (NDVI) from a multispectral image of a Landsat 7 image taken on  
2 Oct 22, 2013 after reflectance correction and ISODATA analysis (Chander et al., 2009; Hossain  
3 et al., 2009).

4 Given the lack of detailed information about the buildings and construction materials, an area  
5 reduction factor of 20% was applied to account for the influence of buildings on the flow. Area  
6 reduction factors are used in FLO2D to reduce the flood volume storage on grid elements due to  
7 buildings or topography (FLO2D, 2012). Although FLO2D allows the inclusion of buildings and  
8 obstacles that can affect the inundation trajectory, it was not clear in this work if the buildings of  
9 Huaraz are strong enough to support the impact and, thus, deviate the flow. In some areas,  
10 especially near the river, it is highly probable that the flow will destroy the buildings, but further  
11 from the river that may be less likely to happen.

12 Flood intensity is determined by the resulting flow depth and velocity in Huaraz. Various methods  
13 of determining the flood intensity from the flood depth and velocity have been developed. The  
14 Austrian method (Fiebiger, 1997) uses the total energy of flow as the indicator of intensity. The  
15 US Bureau of Reclamation (USBR, 1988) uses a combination of depth and velocity and  
16 differentiates these for the impact on adults, cars, and houses. The Swiss method (OFEE et al.,  
17 1997) defines intensity, independent of the object subjected to the hazard, as a combination of  
18 depth and the product of depth and velocity.

19 In this work, the Swiss method is adopted to determine flood intensity as adapted for use in  
20 Venezuela, where intensity thresholds were calibrated with field data from the 1999 alluvial floods  
21 in Venezuela (PREVENE, 2001; García et al., 2002; García et al., 2005). Applying this method  
22 requires simulating the different events to predict the spatially-distributed maximum depths and  
23 velocities for each event, then transferring these results to GIS where a flood intensity map for  
24 each event is created by applying the intensity categorization criteria, low, medium or high (Table  
25 2), to each grid cell in the map.

### 26 **3.6 Hazard identification**

27 Flood hazard is a function of intensity and likelihood of an event. In this case, the event is the  
28 process chain resulting from an avalanche falling into Lake Palcacocha. The level of water in the  
29 lake then determines the resulting wave that may or may not overtop the damming-moraine. To

1 determine flood hazard, normally probability would be the term used instead of likelihood, but  
2 there is not enough data (i.e., recorded avalanche events) to assign probabilities to the different  
3 avalanche events and other processes in the hazard chain; therefore, in keeping with other similar  
4 studies (e.g. Huggel et al., 2004), a qualitative probability, or likelihood, is used. Likelihood is  
5 inversely related to avalanche magnitude; i.e., as discussed previously, large avalanches are less  
6 likely to occur than small avalanches. The flooding intensity for various likelihood events are used  
7 to prepare a preliminary hazard map that will allow communication to the affected community of  
8 the potential hazard at various locations and can facilitate planning, regulation, and zoning based  
9 on the map (O'Brien, 2012).

10 Following Schneider et al. (2014), Raetzo et al. (2002) and Hürlimann et al. (2006) the debris flow  
11 intensities have been classified into three classes, and an intensity-likelihood diagram was used to  
12 denote three preliminary hazard levels (Table 3). *High hazard* - people are at risk of injury both  
13 inside and outside buildings; a rapid destruction of buildings is possible. *Medium hazard* - people  
14 are at risk of injury outside buildings. Risk is considerably lower inside buildings. Damage to  
15 buildings should be expected, but not a rapid destruction. *Low hazard* - people are at slight risk of  
16 injury. Slight damage to buildings is possible. When multiple scenarios are considered, the highest  
17 hazard value for each cell is taken to create the preliminary hazard map (Raetzo et al., 2002).

18

## 19 **4 Results**

### 20 **4.1 Avalanche simulation**

21 The three avalanche events (large, medium and small) were simulated in RAMMS. The maximum  
22 heights of the avalanche material entering the lake range from 6 m for the small avalanche to 20  
23 m for the large avalanche, and the maximum velocities range from 20 m s<sup>-1</sup> for the small avalanche  
24 to 50 m s<sup>-1</sup> for the large avalanche. The RAMMS model simulation period was 60 seconds. The  
25 avalanches take from 33 to 39 seconds to reach the lake and the portion of the mass released that  
26 reaches the lake within the 60 second simulations ranges from 60 to 84% (Table 4).

## 1 **4.2 Lake simulation**

### 2 **4.2.1 Current lake level scenario**

3 For the three avalanche events listed in Table 2, FLOW3D simulations of the resulting wave  
4 generation, propagation and overtopping of the damming-moraine were run with the lake at the  
5 current level of 4562 m. The wave simulations were analyzed for maximum wave height  
6 (measured in m above the initial lake surface) and compared to the wave heights calculated by the  
7 Heller and Hager (2010) method. Overtopping wave discharge hydrographs were calculated at the  
8 moraine crest mid-way between the artificial dam and the 1941 breach (Figure 3), and these  
9 hydrographs were used as calibration parameters for the dynamic breach model and as inputs to  
10 the downstream inundation model. The key results are summarized in Table 2 for each avalanche,  
11 including the overtopping volume, flow rate and wave height as the wave overtops the damming-  
12 moraine.

13 As the avalanche impacts the lake, it generates a wave that propagates lengthwise along the lake  
14 towards the damming-moraine and attains its maximum height when it reaches the shallow portion  
15 at the western end of the lake. The wave heights are shown in Table 4 for the height of the wave  
16 above the moraine crest at the point of overtopping and for the maximum mid-lake wave height.  
17 Although the mid-lake wave heights from FLOW3D are of the same order of magnitude as those  
18 calculated using the Heller and Hager (2010) method, the FLOW3D wave heights are all larger,  
19 with the difference in wave heights up to 13.3% for the large avalanche, and the difference is  
20 greater for small and medium avalanches. This may be an indication that the small and medium  
21 FLOW3D simulations overestimate the momentum transfer to the lake in the wave-generation  
22 process. However, the FLOW3D simulations are able to reproduce the avalanche characteristics  
23 of the RAMMs model as the avalanche enters the lake and account for lake bathymetry, likely  
24 giving more accurate results than the empirical method. In the FLOW3D results, the maximum  
25 wave height is attenuated approximately 30% before it reaches the damming-moraine. Normally,  
26 there would be a significant increase in wave height with the run-up against the terminal moraine,  
27 but because of the high dissipation of energy on the western end of the lake where it becomes  
28 shallow, this effect is somewhat lessened.

29 Looking in more detail at the wave propagation in the large avalanche scenario, there are two peaks  
30 in the wave height. The initial peak is about 1/3 of the way across the lake, corresponding to the

1 empirical equations, and a higher peak occurs when the wave encounters the shallow portion of  
2 the lake. This is the beginning of the run-up process that culminates in the overtopping of the  
3 moraine, where the wave gains height as the water depth decreases.

4 The wave run-up causes a significant amount of water overtopping the damming-moraine. Figure  
5 6 shows that the large avalanche results in an overtopping wave discharge hydrograph with a peak  
6 of about  $63,000 \text{ m}^3 \text{ s}^{-1}$  approximately 60 s after the avalanche fluid is released and a smaller peak  
7 of  $6,000 \text{ m}^3 \text{ s}^{-1}$  due to a reflected wave at about 200 s. The total overtopping volume was  $1.8 \times 10^6$   
8  $\text{m}^3$  for the large avalanche and  $0.15 \times 10^6 \text{ m}^3$  for the small avalanche (Table 4). The duration of  
9 the initial wave of the avalanche events is about 100 seconds (large avalanche), 70 seconds  
10 (medium avalanche), and 50 seconds (small avalanche).

#### 11 **4.2.2 Lake mitigation scenarios**

12 Two lake lowering or mitigation scenarios (with lake levels at 15 m and 30 m below the current  
13 water level) were simulated to determine the impact on the moraine overtopping. Simulations for  
14 all three avalanche sizes were repeated for each lake level and show that the overtopping wave  
15 volume as well as the peak discharge of the wave are incrementally smaller as the lake is lowered  
16 (Table 4). Although the overtopping volumes and peak flow rates decrease with incremental  
17 lowering of the lake, the overtopping wave heights above the artificial dam increase. This is due  
18 to several factors. First, as the point of avalanche impact is at a lower elevation with lowered lake  
19 levels, there is more momentum in the avalanche fluid when it enters the lake. Secondly, the stored  
20 volumes in the lake lowering scenarios are smaller, so the momentum transfer to the lake per unit  
21 volume is higher, thus producing taller waves.

22 Although overtopping cannot be entirely prevented for the large avalanche events, even by  
23 lowering the lake up to 30 m, the small avalanche shows no overtopping of the terminal moraine  
24 for 30 m lake lowering, and the overtopping volume for the medium avalanche scenario is reduced  
25 by 90% compared to the current level scenario. Overtopping is not avoided entirely for the 15 m  
26 lake-lowering scenario; however, the overtopping flow rates and volumes are reduced by about  
27 60% and 80% for the medium and small avalanches, respectively, for 15 m lake lowering.



## 1 **4.3 Moraine erosion simulation**

### 2 **4.3.1 Hydrodynamic model**

3 Dynamic simulations were made in BASEMENT using worst-case soil conditions described above  
4 (Table 1) and the large and medium avalanche wave dynamics to assess the erosion and potential  
5 breach of the damming-moraine at Lake Palcacocha. To validate the use of the two-dimensional  
6 BASEMENT model instead of the full three-dimensional FLOW3D model, the simulation results  
7 of the two models were compared using the peak differences between the mass and momentum  
8 fluxes and the normalized root mean squared error (NRMSE) (Table 2 - Table 5 in revised paper).  
9 The upstream boundary condition of the BASEMENT model was adjusted by varying inflow  
10 energy slopes to force the BASEMENT model to match the mass and momentum fluxes. Peak  
11 mass flux differences are low (ranging from 0.04% to 1.3%). Differences in peak momentum  
12 fluxes, however, show higher discrepancies. The NRMSE indexes assess the behavior of the entire  
13 hydrographs of mass and momentum fluxes and show a similar pattern to that of the peak fluxes,  
14 with errors between 2.0% and 3.8% for mass flux and 3.2% to 5.1% for momentum fluxes.  
15 Considering the extreme peaks of these simulations, the differences seem reasonable, making the  
16 corresponding BASEMENT models a good hydrodynamic base on which to build the erosion  
17 models (see next section). The relative agreement of the overtopping hydrographs between the  
18 BASEMENT and FLOW3D models shows that it is possible to replicate reasonably well the three-  
19 dimensional characteristics of avalanche-generated waves in a two-dimensional SWE model by  
20 exaggerating the energy slopes of upstream boundaries.

### 21 **4.3.2 Hydro-morphodynamic model**

22 Despite poor erosion resistance of the hypothetical soil matrix used in the simulations of the Lake  
23 Palcacocha damming-moraine, the results from the erosion simulations in BASEMENT with the  
24 lake at its current level indicate that a breach and total moraine collapse is extremely unlikely to  
25 occur. Both the large and medium avalanche events result in a no-breach development. Intense  
26 erosion takes place at the distal face of the moraine, where large-avalanche waves cause significant  
27 damage. The bed elevation of the outlet channel is lowered by up to 36 m at the distal face of the  
28 moraine; however, this vertical erosion does not propagate backwards toward the lake. Any  
29 significant erosion remains 270 m away from the lake surface with no significant erosion and  
30 deposition areas occurring over the moraine crest (Rivas et al., 2015). The apparent moraine

1 stability seems to come from morphologic patterns the moraine geometry, not from  
2 morphodynamic erosion resistance; the moraine does not fail in spite of its the very erosive soil  
3 representing it in the hydro-morphodynamic model matrix. The peak flows at the toe of the Lake  
4 Palcacocha damming-moraine (see Figure 3) have been attenuated to less than 50% of the peak at  
5 the crest of the artificial dam.

6 The simulated scenario shows that a complete moraine failure with a large avalanche is extremely  
7 unlikely, and any erosion that occurs as the wave passes the moraine does not significantly affect  
8 the overtopping hydrographs. The large avalanche event is the worst case, so if it doesn't fail then,  
9 it shouldn't fail for the medium and small avalanche events. The results from the FLOW3D  
10 simulations were used as inputs to the downstream inundation model in FLO2D.

#### 11 **4.4 Inundation simulation**

12 Figure 1 shows the locations of 5 cross-sections downstream of Lake Palcacocha where  
13 hydrographs are reported from the FLO2D simulations. Figure 7 and Table 6 show the results of  
14 the simulation of the large avalanche with the current lake level. At cross-section 1, the hydrograph  
15 is still similar to the original hydrograph at the lake with a high-intensity peak flow that is of  
16 relatively short duration. The flow is quickly attenuated as it moves downstream, and the  
17 hydrograph at cross-section 2, located just upstream of the point where the river canyon narrows  
18 and becomes steeper, has a much lower peak than the overtopping hydrograph at the lake, but it is  
19 of longer duration. This is expected because the river is relatively wide with gentle slopes between  
20 the lake and cross-section 2.

21 Cross-section 4 is located at the entrance to the city of Huaraz. The peak discharge of the large  
22 avalanche event diminishes about 40% between the cross-sections 2 and 4. From the beginning of  
23 the large avalanche event it takes the flood wave about 1.3 h to reach cross-section 4 (Table 6),  
24 and the peak flow arrives shortly after. The peak flow takes about 0.75 h to cross the city to cross  
25 section 5 and the peak is attenuated by about 50% in the crossing. Values for the medium and  
26 small avalanche events are shown in Table 6. They take considerably longer to arrive and cross  
27 the city, but their peaks are attenuated about 50% as well. The resulting maximum flood intensities  
28 in Huaraz are shown in Figure 8 for the current lake level and two lake mitigation scenarios (15 m

1 and 30 m of lake lowering) and each of the three avalanche scenarios. The highest intensity areas  
2 are near the existing channels of the Quillcay River and the Rio Santa on the south side of the river.

### 3 **4.5 Hazard identification**

4 Preliminary hazard identification uses the flood intensity maps (Figure 8) and converts them to  
5 maps showing the hazard level at different points in the city according to the intensity-likelihood  
6 flood hazard matrix shown in Table 3. The resulting hazard is obtained by combining the three  
7 avalanche events into a single preliminary hazard map selecting the highest hazard for each cell,  
8 which reflects the result of all the possible avalanche combinations (Figure 9).

### 9 **4.6 Probable maximum inundation**

10 The BASEMENT modeling results (see Sect. 4.3.2. hydro-morphodynamic model) indicate that  
11 the overtopping wave generated from the large avalanche event does not cause sufficient erosion  
12 to initiate a breach of the moraine and release the lake water, thus rendering a full collapse of the  
13 moraine extremely unlikely. The authors consider this scenario nearly impossible given the current  
14 understanding of the moraine conditions and the extensive modeling of the moraine using  
15 extremely erosive soil characteristics. The decision which scenario to eventually include in a  
16 hazard map is not just a scientific question, but also a political one. The results of the breaching  
17 scenario are included since they are needed in order to assess the worst-case scenario, something  
18 science and engineering must communicate to the decision makers and stakeholders. For the sake  
19 of providing complete information, the probable maximum flood as a result of a full breach of the  
20 damming-moraine at Lake Palcacocha was simulated, assuming this event is the worst possible  
21 scenario that could conceivably occur. This probable maximum flood is estimated by modeling  
22 the event of a full collapse of the moraine following an overtopping wave generated by a large  
23 avalanche that erodes the moraine to the extent that the release of the lake water can maintain the  
24 erosion and create a full breach of the moraine. The HEC-RAS breaching model (USACE, 2010)  
25 was used to simulate the progression of the breaching process and the resulting breaching  
26 hydrograph (Rivas et al., 2015). The inflow hydrograph for downstream simulations of this  
27 scenario was created by combining the large avalanche overtopping wave hydrograph under  
28 current lake level conditions with the HEC-RAS breach hydrograph.

1 The flood intensity resulting from this scenario is illustrated in Figure 10. The flood hazard  
2 is not computed since the likelihood of the medium and small avalanches generating waves capable  
3 of eroding the moraine to the extent of initiating a breaching process are simply too remote to  
4 consider.

#### 5 **4.7 Sensitivity analysis**

6 A sensitivity analysis of the inundation was performed, and it focused on three components: (1)  
7 sediment concentration by volume, (2) rheology of the flow, and (3) roughness.

8 **Sediment concentration:** The sediment concentration is an important factor in simulating the  
9 inundation in Huaraz because it affects the volume of the flow, and consequently the depth of  
10 inundation (Somos-Valenzuela, 2014). A potential GLOF will erode the bank along the river,  
11 especially where lateral moraines are present (cross-section 3), scouring, transporting and  
12 depositing soil many times as the flood moves downstream from the lake to the city. FLO2D does  
13 not represent this process when using the Mudflow module. Additionally, we did not have field  
14 information to perform a study of these effects. Therefore, in this work, a fixed sediment  
15 concentration of 50% by volume was used, which is a good upper limit according to the literature  
16 and the FLO2D developers (FLO2D, 2012), but it may be too high if the material available for  
17 erosion is not sufficient in the inundation path. Analysis of sensitivity to sediment concentration  
18 was performed for the inundation in Huaraz, assessing the affect on velocity and flood stage with  
19 sediment concentrations of 0, 20, 30, 40 and 50% (Somos-Valenzuela, 2014). The flood wave  
20 travel times were similar for all cases, and the depths increased with sediment concentration due  
21 to the increased volumes (an increase of up to 8 m at cross-section 4 for a concentration of 50%  
22 compared to no sediment). Thus 50% concentration was considered a reasonable value to use, and  
23 it gives a conservative result.

24 **Flow rheology:** With regard to the possible effects and limitations in the model settings associated  
25 with different flow rheologies, we identified two major sources of uncertainty: (1) the physical  
26 characteristics of the mixture and (2) the volume of material that will be eroded, transported and  
27 deposited again, a process that may happen many times during the trajectory of the flood. FLO2D  
28 can simulate the behavior of the mixture assuming that it won't change throughout the simulation.  
29 Consequently, it is not able to consider transformations of the flow rheology; however, changes in

1 concentration by volume can change the dynamic viscosity ( $\eta$ ) and yield stress ( $\tau_y$ ) (O'Brien and  
2 Julien, 1988). Additionally, scouring is not simulated in the FLO2D mudflow module, so we  
3 prescribe the concentration by volume to be 50% based on the literature recommendations.

4 The quadratic rheological model used within FLO2D combines four stress components of hyper-  
5 concentrated sediment mixtures: (1) cohesion between particles; (2) internal friction between fluid  
6 and sediment particles; (3) turbulence; and (4) inertial impact between particles, where the  
7 cohesion between particles is the only parameter that is independent of the mixture concentration  
8 or hydraulic characteristics (Julien, 2010:243; O'Brien and Julien, 1988). According to the few  
9 studies of the composition of the Lake Palcacocha moraine (Novotný and Klimeš, 2014), the  
10 cohesion can be considered nearly equal to zero, which implies that the resulting mixture would  
11 have low yield stress and dynamic viscosity. Consequently, from the list of 10 soils presented in  
12 the FLO2D manual (FLO2D, 2012: Table 8, p. 57), we selected parameters that give a low yield  
13 stress and dynamic viscosity (Glenwood 2). In addition, a sensitivity analysis was performed using  
14 the parameters for the other soils listed in Table 1 (Aspen Pit 2, Glenwood 1, and Glenwood 3 with  
15 higher dynamic viscosities and yield stresses, and Glenwood 4 with much higher values). The  
16 results of the sensitivity analysis (FLO2D simulations) show that the flood arrival time at cross  
17 section 4 varies from 1.05 to 1.32 hours (compared to 1.32 hours with Glenwood 2 parameters,  
18 see Table 6 in original paper). The peak flow varies from 1954 to 3762  $\text{m}^2 \text{s}^{-1}$  (compared to 1,980  
19  $\text{m}^3 \text{s}^{-1}$  using Glenwood 2). The Glenwood 4 parameters result in the shorter arrival time (somewhat  
20 counter-intuitively) and higher peak value. Therefore, the rheology, which is a function of the  
21 concentration of the mixture and the soil characteristics, does affect the travel time and the peak  
22 flows. The results are not expected to be highly sensitive if the dynamic viscosity were to be lower  
23 than what was assumed (Glenwood 2), which is expected from the few soil studies in the area.

24 The model results show that the flood takes about 45 minutes to cross the city (travel of front of  
25 inundation between cross-section 4 and 5) and the peak flow takes 55 minutes to cross the city.  
26 The inundation spreads through the city diffusing the peak flow and reducing it considerably.  
27 Sensitivity analysis showed that increasing the dynamic viscosity, from Glenwood 2 to Glenwood  
28 4, the flow travels faster, arriving at the city 17 minutes earlier, crossing the city in 36 minutes,  
29 with the peak flow taking 45 minutes to cross the city. Glenwood 2 and 4 are the lower and higher  
30 end, respectively, for the dynamic viscosity parameters used in the sensitivity analysis.

1 **Roughness:** The impact of roughness was analyzed in the dissertation of Somos-Valenzuela  
2 (2014) who concluded that travel time is sensitive to roughness, increasing by 1.5 hours for travel  
3 from the lake to cross-section 4 if the roughness is increased from 0.1 to 0.4. Also, the peak flow  
4 is inversely proportional to the roughness, so lower roughness results in a slightly higher peak (less  
5 than 10% difference in peak flow for 0.1 vs. 0.2 roughness coefficients) (Somos-Valenzuela,  
6 2014). When the roughness within the city is reduced to 0.02, the minimum value recommended  
7 for asphalt or concrete (0.02-0.05) (FLO2D, 2012) and the 20% area reduction factor is removed  
8 (so the flood is limited only by the topography), the inundation takes 22 minutes to cross the city,  
9 50% of the originally computed time. This is an unrealistic value since it considers the entire land  
10 cover of the city to be asphalt with no disturbances, buildings, streets, trees, debris, etc.; however,  
11 this can be considered a minimum possible time for the flood to cross the city. If a roughness value  
12 of 0.05 is used, then the inundation takes 26 minutes to cross the city, and if 0.1 is used, a low but  
13 more realistic value, the flood takes 36 minutes to cross the city. Thus, the travel time across the  
14 city is more sensitive to changes in roughness values than rheology characteristics.

15 The relative impacts of the GLOF process components can be seen by analyzing the inundation in  
16 the city of Huaraz for each of the scenarios simulated. The avalanche size may have the most  
17 significant impact on downstream flood hazard. With the lake at its current level, the affected area  
18 in Huaraz for the small avalanche scenario (0.7 km<sup>2</sup>) is approximately 35% of the area potentially  
19 affected by the large avalanche (2.0 km<sup>2</sup>). The other process that could significantly influence the  
20 flood hazard in the city is the erosion of the damming-moraine. Although results from this work  
21 indicate that a complete moraine failure is extremely unlikely, the possibility of a catastrophic  
22 breach cannot be categorically excluded based on existing evidence. If such a breach were to occur,  
23 the inundated area could increase to 4.93 km<sup>2</sup>, almost 246% more than the large avalanche–no  
24 breach scenario (2 km<sup>2</sup>). Considering the results of the lake lowering mitigation scenarios, the  
25 reduction in hazard area in Huaraz is mostly in the high hazard zones (see Table 7). There is a 27%  
26 and 45% reduction in the high hazard area (compared to the current lake level) when the lake is  
27 lowered 15 or 30 m, respectively.

## 1 **5 Discussion**

### 2 **5.1 General discussion**

3 In this paper, each step in the hazard process chain that could lead to inundation of Huaraz from a  
4 GLOF from Lake Palcacocha has been simulated. Of the simulation methods used in this work,  
5 the lake hydrodynamics and moraine erosion models are advancements beyond what has been  
6 previously reported for GLOF hazard process chain simulations. The use of a fully three-  
7 dimensional hydrodynamic model for simulating wave generation, propagation, run-up and  
8 overtopping of the damming-moraine allows predictive modeling of the process chain through  
9 better representation of the physical processes. Other studies (e.g., Schneider et al., 2014) have  
10 used a past event to calibrate the models and then used those calibrations for predictive modeling  
11 of other scenarios. When data for past events are not available, the three-dimensional model can  
12 help overcome the limitations of two-dimensional SWE models. Better representation of the  
13 physical processes in the model (i.e., three-dimensional non-hydrostatic) makes the models useful  
14 for predictive purposes without a heavy reliance on calibration. Modeling for predictive purposes,  
15 such as that presented in this paper, are useful for analyzing potential GLOF impacts and mitigation  
16 strategies.

17 The general lack of field data regarding actual GLOF events leads to many unknowns about the  
18 processes, particularly processes related to avalanches, lake dynamics and moraine erosion.  
19 Previous simulations of GLOFs have focused on calibrating upper-watershed processes based on  
20 post-event observations (Schneider et al., 2014), but there is very little information on avalanche  
21 characteristics, magnitude of avalanche-generated waves (Kafle et al., 2016), or erosive  
22 capabilities of overtopping waves on which to base validation of these simulated processes. There  
23 is still a considerable amount of uncertainty in the 3D modeling approach for avalanche-generated  
24 waves. Nonetheless, even post-event field studies of GLOF waves have difficulty accurately  
25 characterizing the wave magnitudes. The 3D modeling approach presented in this paper is intended  
26 as an alternative to partially overcome the absence of field data from a GLOF event at the location  
27 of the study.

## 1 **5.2 Model calibration**

2 Because field data are not available, we attempted to counteract the inability to calibrate the models  
3 by using the best available physical representations in our modeling approach. The 3D  
4 hydrodynamic model and the hydromorphodynamic model of moraine erosion can give us a better  
5 understanding of the likely outcomes of these processes than models that require extensive  
6 calibration (e.g., 2D SWE models and breach simulations such as reported in Rivas, et al. (2015)).  
7 This is not to say that these models are free from significant uncertainties, but as a model provides  
8 better mechanisms to represent the underlying physical phenomena, uncertainties move from the  
9 model engine to the physical initial and boundary parameters, reducing the amount of physical or  
10 empirical assumptions. Caution is required in any case because lacking a means of  
11 calibration/validation, these results represent estimations that might deviate from reality without  
12 proper analysis or judgment.

13 Simulations of lake dynamics with a three-dimensional non-hydrostatic model (FLOW3D) and a  
14 two-dimensional SWE model (BASEMENT) indicate that the SWE approximation is not adequate  
15 to simulate waves generated by avalanches because of the large energy dissipation due to  
16 significant vertical accelerations. Two-dimensional hydrostatic models may be adequate for  
17 simulating past events where calibration parameters based on field data may be used to overcome  
18 the approximations in the SWE model (Schneider et al., 2014), but it is important that calibration  
19 be performed at appropriate points in the model to account for energy dissipation as the wave  
20 propagates across the lake. The results from the BASEMENT simulations suggest that, without  
21 careful setting and adjustment of the model's boundary conditions, two-dimensional models might  
22 produce unrealistic results for wave driven phenomena that underestimate the magnitude of an  
23 event. Reference simulations, like those from three-dimensional hydrodynamic models, may help  
24 to overcome limitations on the two-dimensional models and turn them into more flexible and  
25 efficient tools for erosion and breach failure assessment.

26 The primary limitation of the lake hydrodynamic model arises from representing an avalanche  
27 entering the lake as a volume of water, rather than a combination of rock, ice and snow (Kafle et  
28 al., 2016). The wave model calibration method involves controlling the height and depth of the  
29 release area in order to influence the fluid height and velocity in the model as the avalanche enters  
30 the lake. This helps to overcome the limitations of substituting water for the avalanche fluid



1 mixture, but the water representation does not dissipate the energy in the same way as the true  
2 avalanche mixture, and the mixing of the avalanche fluid with the lake is not accurately represented  
3 in the model.

4 The lake model has a considerable amount of uncertainty. The greatest sources of uncertainty are  
5 the avalanche characteristics (inputs to the lake model) and the wave generation. The processes  
6 associated with wave generation from avalanche impact are poorly understood, and current model  
7 limitations do not allow for an avalanche to be simulated with its actual flow characteristics  
8 (rheology, density, etc.) in the same environment as the lake dynamics. Therefore, it is difficult to  
9 represent wave generation in a fully physical manner. The avalanche characteristics (depth and  
10 velocity) have a significant impact on the wave characteristics and moraine overtopping  
11 hydrograph. Additionally, the method of representing the avalanche impact boundary condition  
12 may overestimate the momentum of the inflow; the result of this may be somewhat larger wave  
13 height, but the greatest impact is in the peak flow and total volume of the overtopping wave. The  
14 highest estimates of the overtopping wave characteristics are presented in the paper to illustrate a  
15 worst-case scenario, but it is likely that the actual magnitude of an avalanche generated wave may  
16 be less than what is reported here.

### 17 **5.3 Worst-case event simulation**

18 The moraine erosion simulations used a worst-case approach, depicting the moraine as a structure  
19 with very low erosive resistance. Therefore, the resulting moraine erosion is overestimated, i.e.,  
20 erosion depth, width, length, and growth rate. Thus, the simulations sacrifice accuracy in modeling  
21 the erosion process to gain confidence in predicting the potential for moraine breaching and  
22 collapse. The erosion simulation results suggest that the Lake Palcacocha damming-moraine has  
23 adequate stability to resist erosion induced by large waves, since the modeled erosion does not  
24 reach from the distal face back to the lake, which would allow the lake water to flow through the  
25 breach and accentuate the erosion process and lead to possible moraine failure. The main source  
26 of erosive resistance in the simulations is from the morphology of the moraine (e.g., large width  
27 to height ratio, long crested dam, and gentle slope of distal moraine face) and not from soil  
28 resistance. Previous qualitative assessments of the Lake Palcacocha moraine (Emmer and Vilímek,  
29 2013) and similar structures at other lakes (Worni et al., 2014) assigned very low probabilities of  
30 failure of the moraine, but did note its high susceptibility to wave overtopping. This study,

1 however, provides the first quantitative assessment of possible breach failure for the damming-  
2 moraine at Lake Palcacocha, reinforcing results from the qualitative assessments by using  
3 numerical simulations that account for the morphology of both the lake and moraine in a two-  
4 dimensional modeling scheme.

5 The functions in BASEMENT to simulate erosion come from empirical equations of sediment  
6 transport developed for fluvial environments. Due to their empirical nature, the equations depend  
7 on calibration to achieve accurate results of erosion and deposition rates. Worni et al. (2012)  
8 showed that BASEMENT can achieve realistic results using soil parameters that resemble actual  
9 moraine properties. The bed-load transport model used in this paper (Meyer-Peter and Müller,  
10 1948) has been derived in different forms since its first release to reverse the model's tendency of  
11 over predicting erosion. Newer bed-load models address this problem by applying a direct  
12 reduction factor on resulting transport rates or adding hiding functions to account for multi-grain  
13 soil matrixes (e.g. Ashida and Michiue, 1971; Wu et al., 2000). Additionally, the two-dimensional  
14 limitation of BASEMENT restricts its application for problems where vertical accelerations are  
15 relevant, or vertical flow distribution is not uniform. Under these latter conditions, BASEMENT  
16 needs three-dimensional simulations to serve as calibration parameters before applying the model  
17 to predict erosion and breach formation.

18 Even though a prescribed terminal moraine collapse scenario was simulated, it was not included  
19 in the preliminary hazard map for two reasons. First, the complete collapse scenario is based on  
20 the premise that we should consider a worst case scenario, but we could not initiate the moraine  
21 collapse using our numerical approach; even when a large overtopping wave and highly erosive  
22 materials were assumed, the width of the moraine is simply too great, and the erosion does not  
23 extend from the distal face of the moraine back to the lake. Therefore, we artificially prescribed  
24 and simulated the moraine collapse. Using empirical equations we determined the time that the  
25 collapse will take and the hydrograph was calculated following hydrodynamic constraints as  
26 indicated in Rivas *et al.* (2015). Based on these modeling results it is extremely unlikely that the  
27 collapse will occur, but it cannot be completely disregarded. Secondly, given the magnitude of the  
28 extremely unlikely breach scenario results, it is important to avoid creating confusion as a result  
29 of misinterpretation of the results. People in Huaraz should decide if they want to consider the  
30 worst case scenario in their planning, and this work is limited to informing that decision making  
31 process.

#### 1 **5.4 Comparison to 1941 GLOF**

2 There are still many unknowns about the 1941 event, including the precise lake volume at that  
3 time, underlying bathymetry and pre-GLOF moraine morphology, flood volume and discharge  
4 hydrograph; aerial images and derived historical maps represent the only sources of information,  
5 known to the authors, about the physical characteristics of the 1941 GLOF, providing at least a  
6 rough visual estimation of the flood area. In a qualitative comparison with the GLOF from 1941,  
7 we used a map published by the Instituto Nacional de Defensa Civil (INDECI, 2003) where three  
8 mudflow event extensions are delineated: Aluvion Preincaico, Aluvion Huallac and Aluvion Cojup  
9 1941. In Figure 11 we plot the inundation extension reported in this paper on the map of the 1941  
10 event delineated by INDECI (2003) and confirm that the inundation modeled has reasonable  
11 dimensions in comparison with this historical information. The volume at the time was estimated  
12 to be on the order of 14 million m<sup>3</sup> (Vilimek et al., 2005), which is more than 7 times the volume  
13 that we have calculated for the large avalanche (1.8 million m<sup>3</sup>). This may explain the fact that in  
14 our results the inundation does not pass out of the bank from the Cojup River to the Quilcaihuanca  
15 River in the area where the rivers are very close together near the entrance to the eastern border of  
16 the city. However, these results demand caution; a qualitative comparison only describes potential  
17 differences between simulated and observed flood areas. Because the moraine failure in 1941  
18 changed the upstream conditions at Lake Palcacocha, historical aerial images of flooded areas  
19 constitute no source of information for precise calibration for our model.

#### 20 **5.5 Lateral moraine collapse in 2003**

21 According to Vilimek *et al.* (2005), the lateral moraine collapse that occurred in 2003 at Lake  
22 Palcacocha was due to a wave produced by a landslide on the internal face of the left lateral  
23 moraine that was triggered by extensive rainfall precipitation which over-saturated the moraine  
24 material. The terminal moraine was eroded but it did not breach. A downstream flood was  
25 produced by the water that overtopped the moraine. While this type of landslide from the lateral  
26 moraine is likely to occur again in the future, the work reported here focuses on the potential effects  
27 of an avalanche-generated wave because the magnitude of landslides likely to enter the lake are  
28 less than the avalanche volumes we have considered, and the effect of a landslide-generated wave  
29 may be somewhat mitigated as it propagates diagonally across the lake, whereas an avalanche-  
30 generated wave would enter along the longitudinal axis of the lake and is unlikely to be attenuated

1 by reflections off of the lateral moraines.

2

### 3 **6 Conclusions**

4 There is consensus among local authorities, scientists and specialists that Lake Palcacocha  
5 represents a GLOF hazard with potentially high destructive impact on Huaraz, and this consensus  
6 has been validated by the modeling results presented in this paper. Huaraz previously experienced  
7 a GLOF in 1941 when the outburst from Lake Palcacocha killed about 1800 people (Wegner,  
8 2014). However, there was no previous model that assessed the potential extent of inundation  
9 given the current size of the lake. This work used high-resolution topographic information in a  
10 two-dimensional debris flow model of the inundation below the lake. Several avalanche  
11 magnitudes were used to assess the range of possible inundation and hazard in Huaraz. In addition,  
12 scenarios of based on lake lowering were simulated to determine the mitigation potential of  
13 lowering the lake level.

14 This work has provided a physical analysis of all of the processes in a chain of events from the  
15 summit to the city for a potential GLOF from Lake Palcacocha and determined that there could be  
16 significant impacts in the city of Huaraz. This work has demonstrated advancements in simulation  
17 methods for the lake dynamics and the dynamic erosion process of the damming-moraine that help  
18 further our understanding of this type of event. Based on the results of this work, it can be  
19 concluded that three-dimensional non-hydrostatic simulations of slide-generated waves are  
20 necessary to capture the full effects of these waves and their magnitudes at the point of  
21 overtopping. This study also found that the morphology of the damming-moraine at Lake  
22 Palcacocha may be a more important factor than the soil erosion characteristics in determining the  
23 stability of the moraine and its ability to withstand the high forces of large overtopping waves.

24 Although no sources of calibration exists for a breach event under the current conditions of Lake  
25 Palcacocha, the results showed no sensitivity to drastic variations and assumptions regarding the  
26 composition of the soil matrix. A governing assumption on the weakest possible soil composition  
27 led to no collapse and only partial damage during wave events. This approach worked well due to  
28 the characteristics of the moraine-lake system at Lake Palcacocha (mainly its moraine  
29 morphology). However, different conditions at other glacial lakes might require richer calibration  
30 and sensitivity considerations, demanding caution for applying this method to different cases.

Comment [DCM7]: GC-3: Added text

1 The results indicate that a GLOF for a large avalanche event takes about one hour and twenty  
2 minutes to arrive at the city (cross-section 4) after the avalanche process starts, and the flood peak  
3 arrives two to three minutes later. The peak crosses the city from in about 45 minutes, expanding  
4 to the north and south as it progresses through the city. Based on the flood intensity, the most  
5 highly impacted areas in the city are near the Quillcay River just to the south of the river. While  
6 the inundated areas for medium and small avalanches are less than the affected area due to a large  
7 avalanche, there is a significant reduction in the high intensity areas for these events. For the large  
8 avalanche event, most of the affected area of the city has a very high hazard level for the current  
9 lake level. With mitigation through lake lowering, the total affected area is reduced (by around  
10 30% for a 30 m lowering scenario), but the greatest impact of lake lowering is that more of the  
11 high and medium hazard zones areas are downgraded to low hazard. The results indicate that Lake  
12 Palcacocha is dangerous if an avalanche occurs, especially since there is no way to prevent an  
13 avalanche from falling into the lake and overtopping waves are expected for all avalanche sizes  
14 with the lake at its current level. The damage could be even more extensive in the extremely  
15 unlikely event of an avalanche and moraine breach.

16 Based on these conclusions, it is recommended an early warning system should be installed in the  
17 basin. This is an urgent matter because a significant area of the city of Huaraz could be impacted  
18 by a GLOF from Lake Palcacocha, and timely warning and evacuation of the population is the best  
19 way to prevent injuries and mortalities. The results of this study indicate that the inundated area  
20 may be reduced through lake lowering, and the highest likelihood event (small avalanche) produce  
21 significantly less inundation with lake lowering. An economic analysis of mitigation alternatives  
22 should be undertaken to determine an optimized lake level that balances cost and potential benefits.

23

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12

13

1 Table 1. Main Parameters Defining the Soil Matrix Used in BASEMENT Simulations of the Lake  
 2 Palcacocho Moraine.

Morphodynamic parameter	Adopted value	Source
Sediment transport formula	MPM single-grain	Meyer-Peter and Müller (1948)
Diameter $d_{50}$	1 mm	Novotny and Klimes (2014)
Porosity	40%	Typical value for spherical sediment
Bed load factor	2	Modified from Wong and Parker (2006) and Worni et al. (2012)
Failure angle of submerged sediment	36.5 degrees	Novotny and Klimes (2014)
Failure angle of dry sediment	77 degrees	Worni et al. (2014)
Failure angle of deposited sediment	15 degrees	Worni et al. (2014)

3  
 4 Table 2. Flood Intensity Classification.

Intensity		Maximum Velocity ( $m s^{-1}$ ) times Maximum Depth (m)			Flood Intensity
		> 1.0	0.2 - 1.0	< 0.2	
Maximum	> 1.0	High	High	High	High
	0.2 - 1.0	High	Medium	Low	Medium
	< 0.2	High	Low	Low	Low

5  
 6

1

2 Table 3. Flood Hazard Classification.

<b>Hazard</b>		<b>Likelihood</b>			<b>Hazard Level</b>
		High	Medium	Low	
		<b>Avalanche Size</b>			
		Small	Medium	Large	
<b>Intensity</b>	High	High	High	High	High
	Medium	High	Medium	Low	Medium
	Low	Medium	Low	Low	Low

3

4

- 1 Table 4. Characteristics of Three Avalanche Events of Different Size as Simulated in RAMMS.  
 2 Overtopping Volume, Flow Rate and Wave Height for Three Avalanche Events as Simulated in  
 3 FLOW3D for the Current Lake Level and Three Lake Mitigation Scenarios. Comparison of mid-  
 4 lake wave heights between Heller and Hager (2010) equations and FLOW3D simulations for 0-m  
 5 lower scenario

	Avalanche Event		
	Large	Medium	Small
<b>Avalanche characteristics in RAMMS</b>			
Avalanche size ( $10^6 \text{ m}^3$ )	3	1	0.5
Maximum depth of avalanche material at lake entry (m)	20	15	6
Maximum velocity of avalanche material at lake entry ( $\text{m s}^{-1}$ )	50	32	20
Time to reach the lake (seconds)	33	36	39
% of mass released that reaches the lake in 60 seconds	84	72	60
<b>0 m lower</b>			
Overtopping volume ( $10^6 \text{ m}^3$ )	1.8	0.50	0.15
Overtopping peak flow rate ( $\text{m}^3 \text{ s}^{-1}$ )	63,400	17,100	6,410
Overtopping wave height above artificial dam (m)	21.7	12.0	7.1
Maximum mid-lake wave height (m) - Heller and Hager (2010)	42.2	21.1	8.8
Maximum mid-lake wave height (m) – FLOW3D	47.8	30.1	19.6
<b>15 m lower</b>			
Overtopping volume ( $10^6 \text{ m}^3$ )	1.6	0.2	0.02
Overtopping peak flow rate ( $\text{m}^3 \text{ s}^{-1}$ )	60,200	6,370	1,080
Overtopping wave height above artificial dam (m)	38.4	27.5	25.1
<b>30 m lower</b>			
Overtopping volume ( $\text{m}^3$ )	1.3	0.05	0
Overtopping peak flow rate ( $\text{m}^3 \text{ s}^{-1}$ )	48,500	1,840	0
Overtopping wave height above artificial dam (m)	60.8	42.5	0

6

1 Table 5 . Fit indices for flow properties at the overtopping zone of Lake Palcacocha (Target cross  
2 section in Figure 5) comparing BASEMENT and FLOW3D simulation results.

Flow property	Fit indices	Scenarios	
		No lake lowering	Lake lowering
Mass flux	Peak mass flux difference (%)*	0.04	1.3
	NRMSE (%)**	3.8	2.0
Momentum flux	Peak momentum flux difference (%)*	7.3	4.4
	NRMSE (%)**	5.1	3.2

3 \* Peak differences refer to relative errors (expressed as percentage) between point measurements of  
4 maximum mass flux and momentum flux for both models (Flow 3D and BASEMENT).

5 \*\* NRMSE = Normalized Root Mean Square Error, accounts for errors across the entire hydrograph of  
6 mass and momentum fluxes.

7

8

1 Table 6. FLO2D Simulation Results at Cross-sections Downstream of Lake Palcacocha for the  
 2 Current Lake Level and a Large Avalanche.

<b>Cross Section</b>	<b>Avalanche size</b>	<b>Arrival time (hr)</b>	<b>Peak time (hr)</b>	<b>Peak discharge (m<sup>3</sup> s<sup>-1</sup>)</b>
<b>1</b>	Large	0.05	0.05	39,349
	Medium	0.08	0.09	4,820
	Small	0.14	0.16	436
<b>2</b>	Large	0.51	0.65	3,246
	Medium	1.07	1.14	347
	Small	2.8	2.88	27
<b>3</b>	Large	0.81	0.84	2,989
	Medium	1.67	1.71	272
	Small	4.57	4.6	19
<b>4</b>	Large	1.32	1.36	1,980
	Medium	2.9	2.97	149
	Small	8.68	8.73	8
<b>5</b>	Large	2.1	2.26	920
	Medium	4.95	5.27	73
	Small	15.8	16.1	4

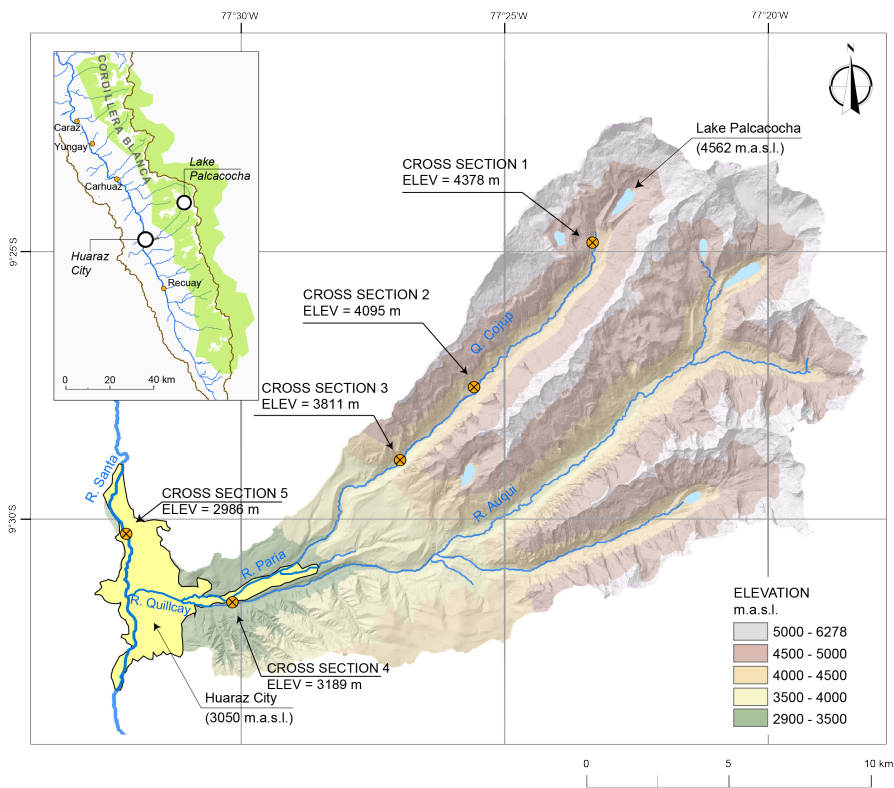
3  
 4 Table 7. Areas of Each Hazard Level corresponding to the Current Lake Level and Two Lake  
 5 Mitigation Scenarios.

<b>Mitigation</b>	<b>Low hazard area (km<sup>2</sup>)</b>	<b>Med. hazard area (km<sup>2</sup>)</b>	<b>High hazard area (km<sup>2</sup>)</b>	<b>Total affected area (km<sup>2</sup>)</b>
0 m lower	0.52	0.05	1.43	2.01
15 m lower	0.61	0.00	1.04	1.65
30 m lower	0.61	0.00	0.79	1.40

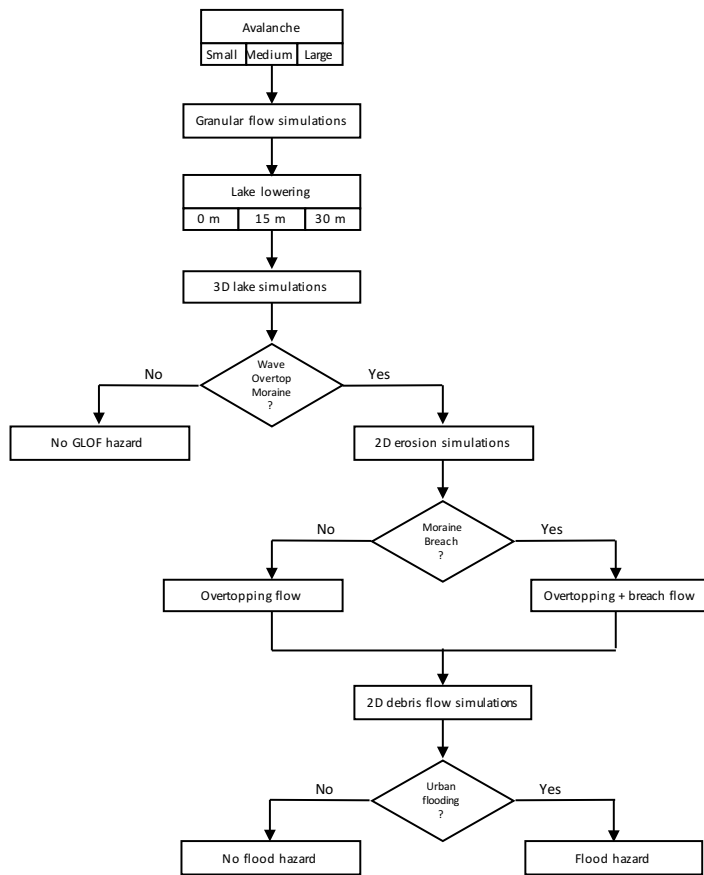
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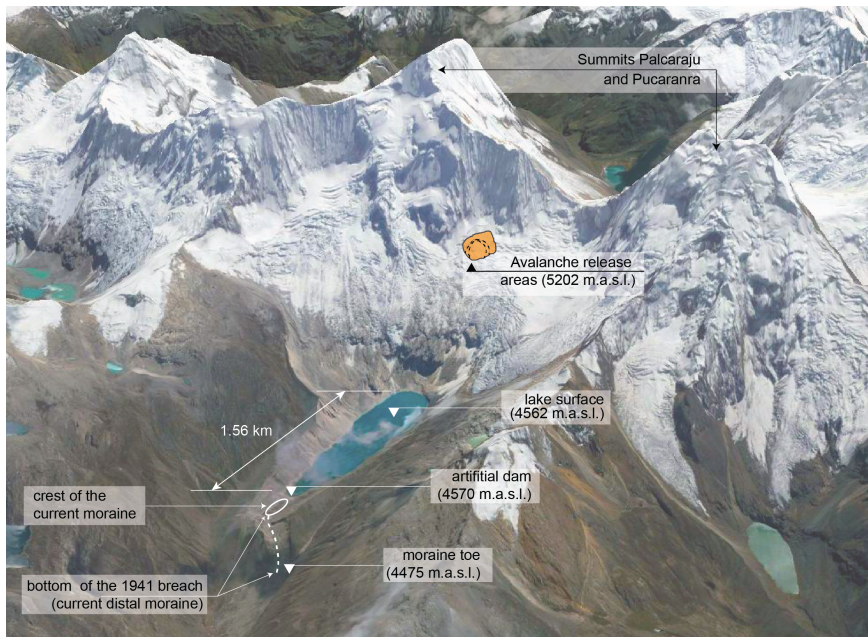


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 2 Figure 1. Map of the study area showing Lake Palcacocha and the city of Huaraz in the Quillcay  
 3 watershed and the Digital Elevation Model (DEM) of Quillcay watershed. The locations where  
 4 hydrographs of the FLO2D simulation results are illustrated are marked as cross-sections.



1  
 2 Figure 2. Flowchart of the hazard process chain for an avalanche triggered GLOF from a glacial  
 3 lake to assess potential downstream inundation.

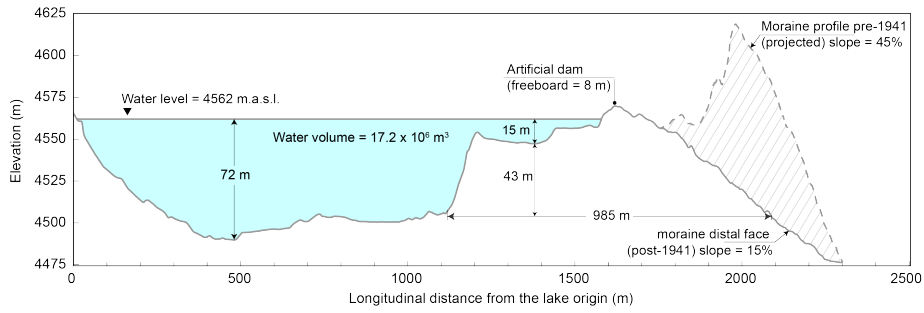
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1  
 2 Figure 3. Lake Palcacocha in 2014 with Palcaraju (6,274 m) on the left and Pucaranra (6,156 m)  
 3 on the right in the background and the 1941 GLOF breach below the lake. Potential avalanche  
 4 release areas located at an elevation of 5202 m to the north east of Lake Palcacocha following the  
 5 main axis of the lake. (Google Earth, 2014).

6  
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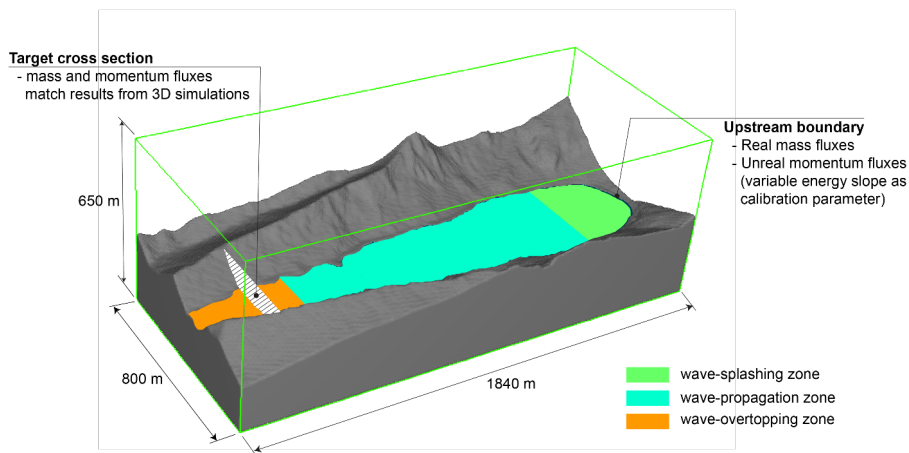
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2

3 Figure 4. Longitudinal profile of Lake Palcacocho and its terminal moraine (factor of vertical  
 4 exaggeration of 5). The moraine profile before the 1941 GLOF exhibited width-to-height ratios of  
 5 6, while the reshaped moraine after 1941 shows width-to-height ratios of 14 and gentler slopes of  
 6 15% (after Rivas et al., 2015).

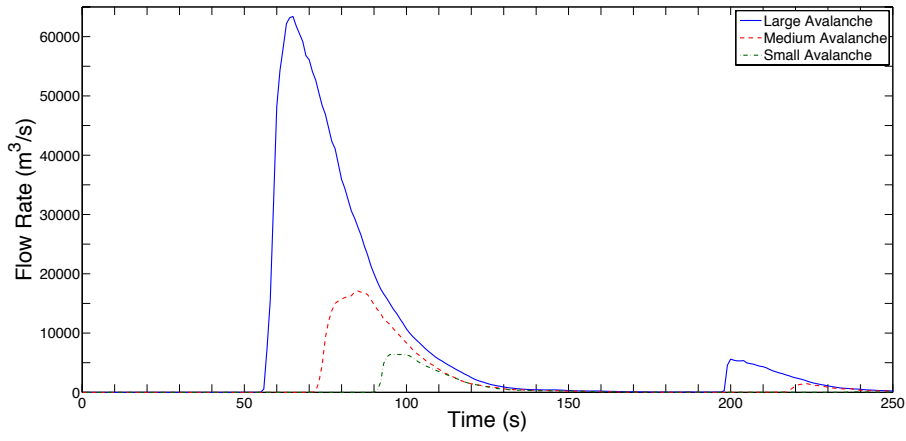
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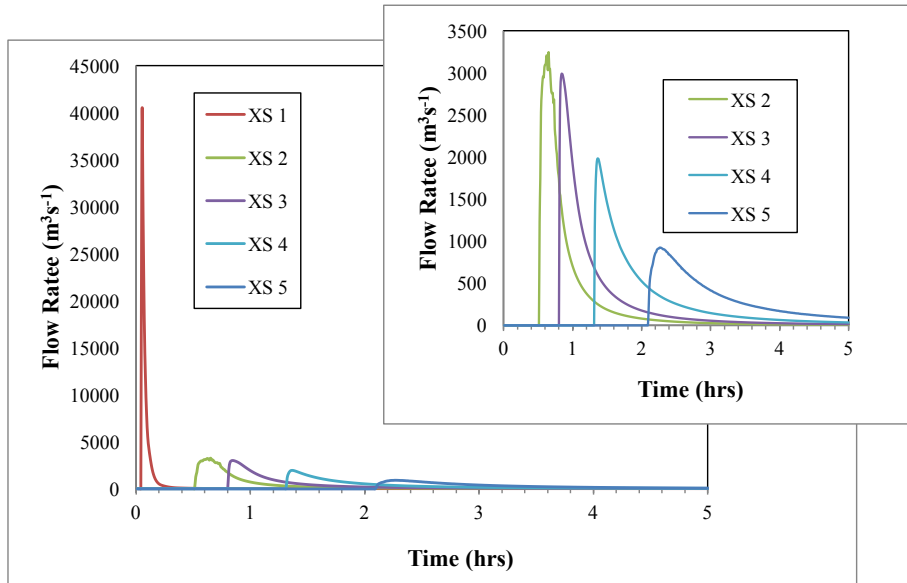
9 Figure 5. Zones of comparison to validate using BASEMENT for wave-driven breach models. The  
 10 length of each zone is conceptual and not precise. The locations of the upstream boundary and the  
 11 target cross section coincide with equivalent flux surfaces in FLOW3D.

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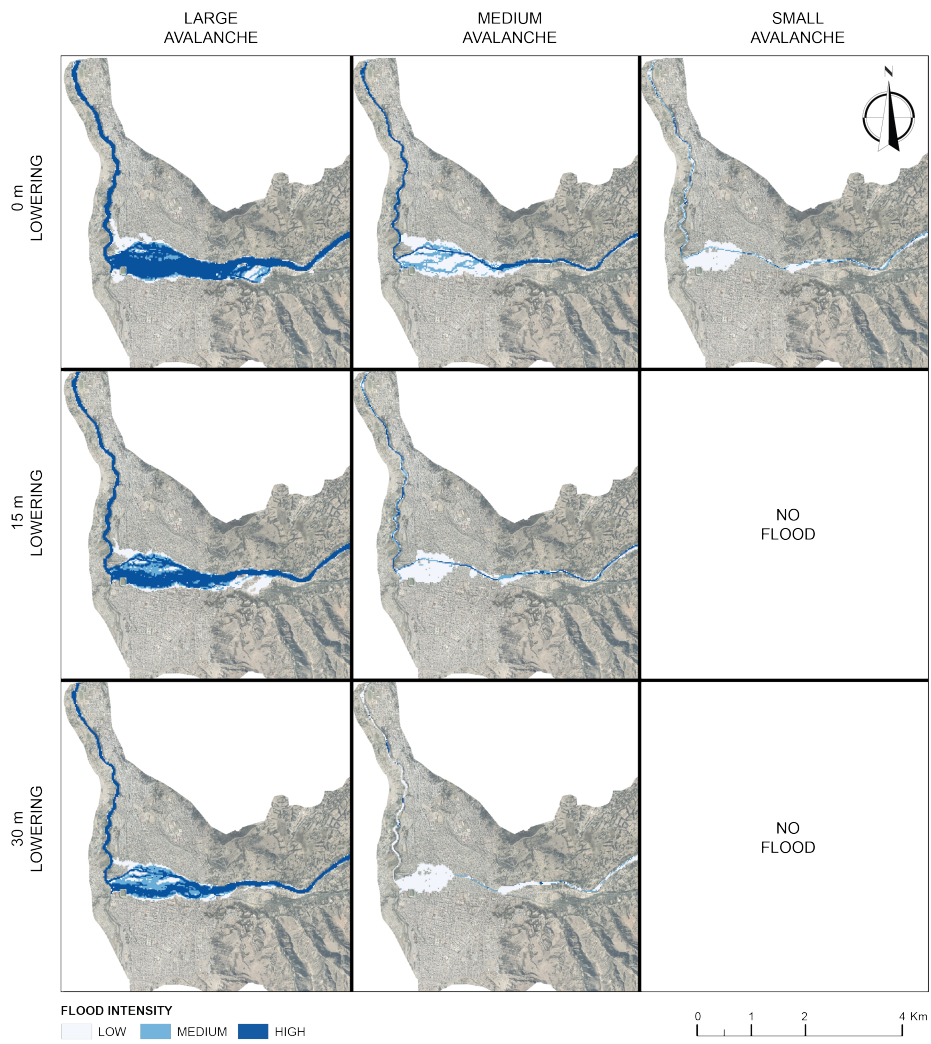


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Figure 6. Overtopping wave discharge hydrographs for the three avalanche events with the lake at its current level.

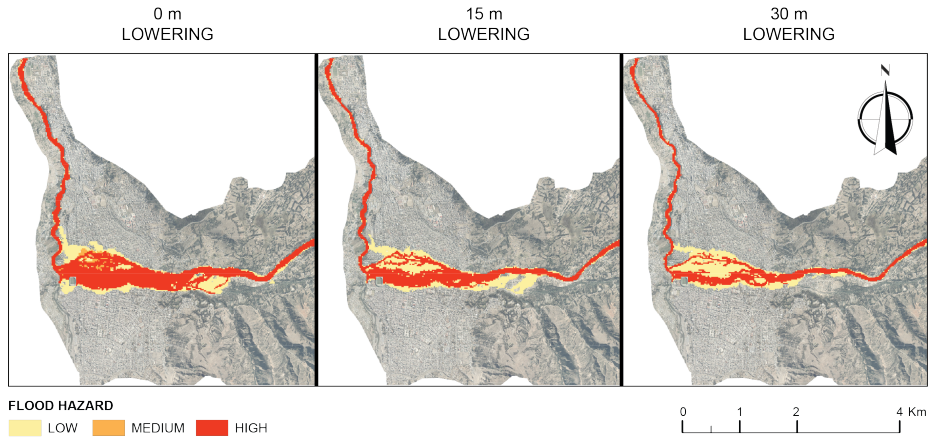


1  
 2 Figure 7. Flood hydrographs at 5 cross-sections downstream of Lake Palcacocha for the large  
 3 avalanche and current lake level scenario. Inset shows results on a larger vertical scale for cross-  
 4 sections 2-5.  
 5



1  
 2 Figure 8. Flood intensity in Huaraz associated with a potential GLOF from Lake Palcacocha for  
 3 scenarios of 0 m of lake lowering (current condition), 15 m lowering and 30 m lowering conditions  
 4 for small, medium and large avalanches.  
 5

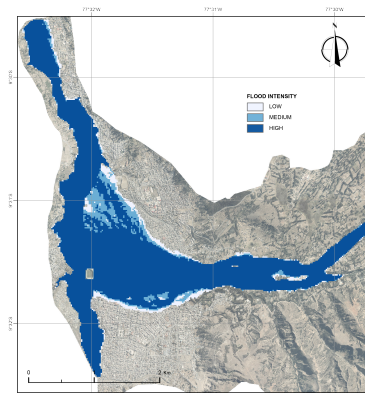
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2

3 Figure 9. Preliminary hazard map of Huaraz due to a potential GLOF originating from Lake  
 4 Palcacocha with the lake at its current level (0 m lowering) and for the two mitigation scenarios  
 5 (15 m lowering, and 30 m lowering).

6



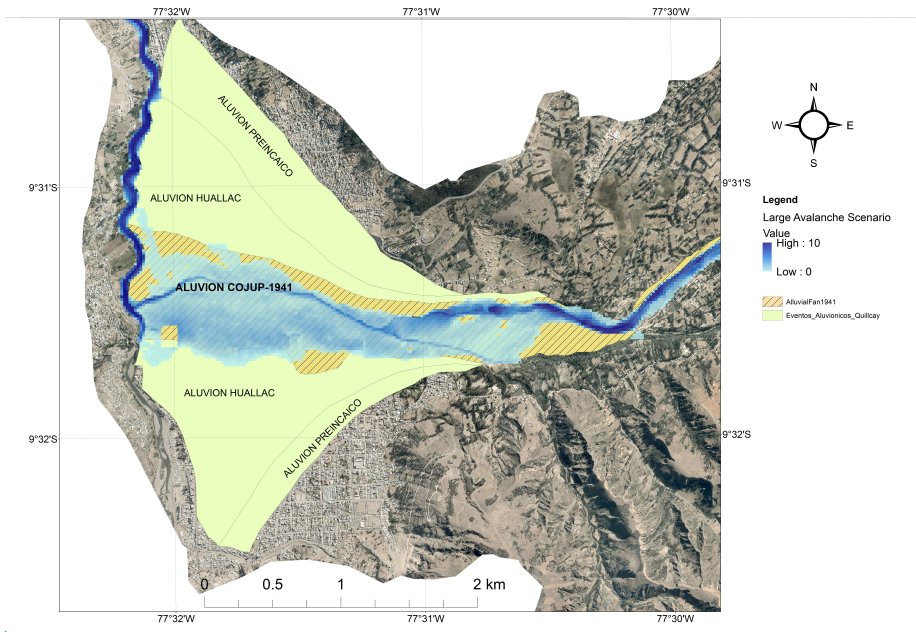
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8 Figure 10. Flood intensity in Huaraz associated with a probable maximum inundation GLOF from  
 9 Lake Palcacocha for the scenario of 0 m lake lowering condition and a large avalanche.

10



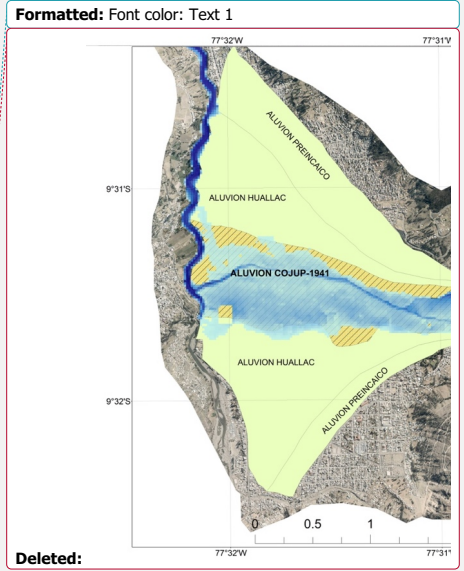
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3 Figure 11. Maps published by INDECI (2003) indicating the extension of past mudflow events  
 4 with the large avalanche scenario superimposed on top of them.

5



Comment [DCM8]: SC-1: The RGB colors should be deleted from the legend.

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