Dynamics of avalanche-generated impulse waves: three-dimensional hydrodynamic simulations and sensitivity analysis

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Abstract. This paper studies the lake dynamics for avalanche-triggered glacial lake outburst floods (GLOFs) in the Cordillera Blanca mountain range in Ancash, Peru. As new glacial lakes emerge and existing lakes continue to grow, they pose an increasing threat of GLOFs that can be catastrophic to the communities living downstream. In this work, the dynamics of displacement waves produced from avalanches are studied through three-dimensional hydrodynamic simulations of Lake Palcacocha, Peru, with an emphasis on the sensitivity of the lake model to input parameters and boundary conditions. This type of avalanche-generated wave is an important link in the GLOF process chain because there is a high potential for overtopping and erosion of the lake-damming moraine. The lake model was evaluated for sensitivity to turbulence model and grid resolution, and the uncertainty due to these model parameters is significantly less than that due to avalanche boundary condition characteristics. Wave generation from avalanche impact was simulated using two different boundary condition methods. Representation of an avalanche as water flowing into the lake generally resulted in higher peak flows and overtopping volumes than simulating the avalanche impact as mass-momentum inflow at the lake boundary. Three different scenarios of avalanche size were simulated for the current lake conditions, and all resulted in significant overtopping of the lake-damming moraine. Although the lake model introduces significant uncertainty, the avalanche portion of the GLOF process chain is likely to be the greatest source of uncertainty. To aid in evaluation of hazard mitigation alternatives, two scenarios of lake lowering were investigated. While large avalanches produced significant overtopping waves for all lake-lowering scenarios, simulations suggest that it may be possible to contain waves generated from smaller avalanches if the surface of the lake is lowered.

1 Introduction

Glacier retreat worldwide has resulted in the emergence and growth of glacial lakes that have replaced ice in the tongue area of many glaciers, and a large number of these lakes pose a hazard or risk of glacial lake outburst floods (GLOFs). GLOFs are common in many parts of the world, and they can be catastrophic to downstream communities and infrastructure. Emmer et

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al. (2016a) have compiled a worldwide database of GLOF events, including approximately 20 events in the Peruvian Andes. Wang et al. (2015b) found that glacial lakes in the central Himalaya have expanded significantly (122.1%) from 1976 to 2010, and and Schwanghart et al. (2016) showed that more than 68% of Himalayan hydropower projects are located on potential GLOF tracks. Allen et al. (2016) performed a first-order assessment of GLOF risk across the Himalayan state of Himachal Pradesh (HP), Northern India, including locations where future lakes might form. They identified areas with potentially high GLOF risk and determined that GLOF hazard is likely to increase in the future with continued deglaciation. Linsbauer et al. (2016) calculated glacier overdeepenings and predicted the emergence of future lakes in the Himalaya and Karakoram in relation to GLOF risk and found approximately 5000 overdeepening locations that could form significant glacial lakes. Cook et al. (2016) studied glaciers in the Bolivian Andes where glaciers have receded about 40% between 1986 and 2014, resulting in an increasing number of proglacial lakes. They identified 25 lakes that pose a potential GLOF threat to downstream communities and infrastructure. The Cordillera Blanca mountain range in Peru has approximately 1900 lakes, and 830 of them have a surface area greater than 5000 m^2 (UGRH, 2014). Of the lakes in the Cordillera Blanca, over 200 are considered new lakes that have formed recently due to glacier retreat (UGRH, 2014). A recent inventory of glacial lakes in the Cordillera Blanca and their susceptibility to GLOFs classifies Lake Palcacocha in the highest level of susceptibility to outburst floods due to mass movements into the lake (Emmer et al., 2016c). Several GLOFs have occurred in the Cordillera Blanca in recent history, and climate change and accelerated glacial retreat have been increasing the GLOF hazard since the end of the Little Ice Age in the late 1800's (Carey, 2010).

GLOFs can be highly destructive because the peak discharges tend to be several orders of magnitude larger than typical outflows from glacial lakes (Benn and Evans, 2010). Moraine-dammed lakes are particularly susceptible to outburst flooding due to the potential for moraine failure that could cause higher GLOF discharges than would occur with just overtopping (Emmer and Cochachin, 2013); however, both moraine-dammed and bedrock-dammed lakes can produce potentially catastrophic GLOFs due to overtopping if there is insufficient freeboard. According to studies that have established basic methods for evaluating potential glacial lake hazards (e.g., Haeberli et al., 1989; Huggel et al., 2004; Wang et al., 2011; Emmer and Vilímek, 2014; Rounce et al., 2016), the primary characteristics that signify a potentially hazardous glacial lake are the presence of overhanging ice and the likelihood of failure of the lake-damming moraine; secondary characteristics that indicate potentially dangerous lakes include the potential for landslides, rock-slides or rock-ice avalanches. However, understanding of the physical processes that can trigger a GLOF event is still limited. The most common GLOF triggers are landslides, avalanches, or ice calving into a lake (Costa and Schuster, 1988; Richardson and Reynolds, 2000; Bajracharya et al., 2007; Awal et al., 2010; Emmer and Cochachin, 2013; Emmer and Vilímek, 2013). These mass movement events can cause large waves that propagate across glacial lakes and may overtop or breach moraine dams.

Several studies have looked at GLOF events after they have happened and attempted to reconstruct the GLOF characteristics. Worni et al. (2014) and Westoby et al. (2014a) review various methods for modeling a typical GLOF process chain. Some researchers have simulated GLOFs with models of the individual processes in the chain (e.g., Klimes et al., 2014; Schneider et al., 2014; Westoby et al., 2014b; Worni et al., 2014; Wang et al., 2015a; Somos-Valenzuela et al., 2016);

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however, the lake dynamics remain one of the most difficult processes to simulate correctly due to the need for a non-hydrostatic model to correctly represent the wave dynamics (Heinrich, 1992; Zweifel et al., 2007; Worni et al., 2014) and the lack of field data for model calibration or validation. Most previous studies have used two-dimensional shallow water equation models (2D SWE models) or empirical models of wave generation and propagation in the lakes that do not effectively represent the physical processes, and our understanding of the uncertainties arising from avalanche-generated wave simulations in GLOF process chain modeling is still very limited. Although they have seldom been studied, evaluating the sensitivities of displacement wave models helps us understand the uncertainties that may arise from wave simulations within GLOF process chain modeling. One difficulty is the lack of data about real events, so the potential hazard and impacts of a GLOF must be estimated from an analysis of the physical conditions and modeling the basic physical processes without the availability of calibration data (Somos-Valenzuela et al., 2016). This paper presents three-dimensional non-hydrostatic simulations of avalanche-generated waves and improves upon previous two-dimensional SWE simulations of avalanche-generated waves in GLOF process chain modeling that must be calibrated with data from past GLOF events (e.g., Schneider et al., 2014). Many glacial lakes that are currently dangerous have not previously outburst, so the use of data from prior GLOF events is not an option at many study sites. Three-dimensional non-hydrostatic models provide better representation of the physical processes within the model than 2D shallow water models, thus reducing the amount of calibration needed; but, 3D non-hydrostatic models have rarely been applied to avalanche-generated waves and GLOF process chain modeling.

The objective of this paper is to gain a better understanding of the behavior of avalanche-generated waves and the factors that influence overtopping discharges. This paper evaluates the relative uncertainties generated in the lake model portion of the GLOF process chain with the goal of improving GLOF hazard assessments. Particular emphasis is placed on analysis of the sensitivity of the lake model to various input parameters and methods for simulating boundary conditions with the goal of shedding light on potential sources of uncertainty in the lake model. An improved understanding of the dynamics of avalanche-generated waves can help advance predictive modeling of potential GLOF events by relying less on model calibration when data from past events are not available, thus enabling better evaluation of possible hazard mitigation strategies at potentially dangerous lakes. It is a significant challenge to predict the impacts of an event that has not yet happened, and predictive simulations inherently carry considerable uncertainty about many event parameters. Nevertheless, this challenge is one that must be undertaken for progress to be made in glacial hazard assessment and analysis of hazard mitigation strategies.

1.1 Lake Palcacocha

GLOFs have been a problem in the Cordillera Blanca for many years (Lliboutry, 1977; Reynolds, 2003; Carey, 2010). The most disastrous GLOF event in the Cordillera Blanca in recent history occurred in 1941 when Lake Palcacocha burst, destroying much of the city of Huaraz and killing approximately 1800 people (Carey, 2010; Wegner, 2014). This event received much notice from national and international media and put the issue of GLOFs at the forefront of national attention in Peru. Huaraz is the most populous city in the Cordillera Blanca region with over 100,000 residents (INEI, 2007 census),

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Deleted: through three-dimensional, non-hydrostatic simulations of the waves and it is once again exposed to a potential GLOF from Lake Palcacocha (Somos-Valenzuela et al., 2016). After the 1941 Huaraz flood, the Peruvian government instituted initiatives to reduce the GLOF risk in the Cordillera Blanca through monitoring of glaciers and glacial lakes and implementing lake safety systems (Carey, 2010). These safety systems typically consist of tunnels to control lake levels, reinforced dams or a combination of the two (Portocarrero, 2014). Scientists and engineers in Peru have several decades of experience managing glacial lakes in the Cordillera Blanca and mitigating GLOF risk (Carey, 2010; Portocarrero, 2014), but current lake management practices are based on studies performed decades ago that have not been updated to account for changes that have occurred since then, primarily increased size and water storage in glacial lakes due to changing climate. The lake safety system implemented at Lake Palcacocha in the 1970's was designed for the size of the lake at the time and did not account for future lake growth. If the present knowledge of climate change existed at that time, perhaps this could have been foreseen; this was not the case, and now the lake is approximately 17 times larger than it was in 1974 (Rivas et al., 2015), rendering the existing lake safety system inadequate for the current lake dimensions (Portocarrero, 2014). The potential threat that Lake Palcacocha currently poses to the residents of Huaraz has been known for many years. Peruvian government institutions have produced several official reports about the situation (INDECI, 2011; ANA, 2013; Valderrama et al., 2013; Espinoza, 2013; INDECI, 2015), and a state of emergency was declared in 2010 (Diario la Republica, 2010; INDECI, 2011). In this paper, Lake Palcacocha is used as a case study to investigate the impact of an avalanche event on the lake dynamics and the ensuing discharge hydrograph from the lake and to study the sensitivity of the overtopping discharge to various input parameters. This paper focuses exclusively on the lake dynamics for avalanche-generated waves and does not consider other parts of the GLOF process chain. The model results for the entire GLOF chain of events are presented in Somos-Valenzuela et al. (2016).

Lake Palcacocha (4562 m) is situated in the Quillcay watershed above the city of Huaraz (Fig. 1). Above the lake are the Palcaraju and Pucaranra glaciers. The steep overhanging ice of the glacier termini in contact with the lake makes it extremely prone to avalanche-generated waves. Additionally, the large volume of water contained in the lake provides a serious threat to downstream areas. The lake is surrounded on three sides by glacial moraines, and the lateral moraines are very tall with slopes up to 80º (Klimes et al., 2016). The southern lateral moraine is prone to landslides into the lake, and a slide from this moraine in 2003 caused minor damage from a wave that overtopped a portion of the lake-damming moraine (Vilimek et al., 2005). The original lake-damming terminal moraine was breached during the 1941 GLOF, and the lake is currently dammed by a smaller basal moraine that lies about 300 m upstream of the 1941 breach. This smaller moraine that currently holds back the lake is approximately 66 m deep, 985 m wide and has a width-to-height ratio of 14.9; this morphology indicates that the lake-damming moraine is very stable (Rivas et al., 2015). A tunnel to maintain a constant lake level of 4562 m (8 m of freeboard) was constructed in 1974 (Reynolds, 2003; Portocarrero, 2014), and two sections of the smaller terminal moraine have been reinforced with concrete to protect them from erosion. Based on a 2009 bathymetric survey, the volume of the lake was approximately 17 million m^3 at that time (UGRH, 2009). The lake has since retreated approximately 200 m more (Rivas et al., 2015), and siphons are currently being used to temporarily maintain the lake an additional 3-5 m lower; however, during the rainy season, the siphon system is often not able to keep up with the rainfall draining into the lake. A

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bathymetric survey undertaken in February, 2016, measured a volume of approximately 17.4 x 10^6 m^3 with a water surface elevation of 4562.88 m (UGRH, 2016). Lake Palcacocha has a deep area adjacent to the glacier with a maximum depth of 72 m and a shallow portion with depths mostly under 10 m extending several hundred meters back from the terminal moraine (Fig. 2).

The potential hazard due to an outburst flood from Lake Palcacocha has been studied by several researchers. Vilimek et al. (2005) discussed the influence of glacial retreat on hazards at Palcacocha and studied the moraine composition and the potential for landslides from the lateral moraines; they also found seepage at the moraine dam. Emmer and Vilimek (2013) used a generalized methodology for GLOF hazard assessment at Lake Palcacocha and 5 other lakes in the Cordillera Blanca, concluding that Lake Palcacocha had the highest hazard level. Emmer and Vilimek (2014) examined mechanisms of the 1941 and 2003 GLOFs at Lake Palcacocha and compared them to other historic GLOFs in the Cordillera Blanca. Emmer et al. (2016b) evaluated the effectiveness of lake safety systems in the Cordillera Blanca and found that the system at Lake Palcacocha resulted in a minimal decrease in GLOF susceptibility, and Emmer et al. (2016c) classified Lake Palcacocha as highly susceptible to GLOFs triggered by mass movements. Klimes et al. (2016) evaluated the lateral moraines surrounding Lake Palcacocha and determined that there is a high potential for landslide-triggered waves in the lake. Rivas et al. (2015) modeled a full moraine collapse using empirical equations and DAMBRK hydraulic simulations, and Somos-Valenzuela et al. (2016) gave the results of simulations of a potential GLOF chain of events and mapped potential hazard levels for the city of Huaraz. This paper focuses on the avalanche boundary conditions, turbulence modeling and grid size and their relative contributions to uncertainty in the lake model used by Somos-Valenzuela et al. (2016) to model the entire GLOF process chain and downstream impacts.

1.2 Impulse Waves Generated from Avalanches and Landslides

The dynamics of avalanche or landslide-generated waves are very complex (Fritz et al., 2004; Worni et al., 2014). In addition, it is very difficult to obtain field measurements of these waves to better understand their dynamics, and most of the data from actual events are estimates based on residual evidence in the field (e.g., run-up on side slopes or moraine erosion). The physical principles governing the mechanics of wave generation and propagation are presented in Dean and Dalrymple (1991). A number of studies have developed empirical models from laboratory simulations and/or field data of avalanche and landslide generated waves (e.g., Kamphuis and Bowering, 1970; Slingerland and Voight, 1979 and 1982; Fritz et al., 2004; Heller and Hager, 2010), but many of the laboratory models use simplified geometries (Heller et al., 2016). Numerical simulations of slide-generated waves have been primarily focused on two-dimensional simulations and simple arrangements (e.g., Rzadkierwicz et al., 1997; Zweifel et al., 2007; Biscarini, 2010; Cremonesi et al., 2011; Ataie-Ashtiani et al., 2011; Ghozlani et al., 2013); but, the two-dimensional shallow water equations (SWE) may not be appropriate for slide-generated waves because of the role that vertical accelerations play in the wave dynamics (Heinrich, 1992; Zweifel et al., 2007). Recent developments in numerical simulations of landslide-generated waves include simulation of multi-phase flows, including a three-dimensional Navier-Stokes Volume of Fluid model (Abadie et al., 2010), a two-phase debris flow model (Kafle et al.,

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2016), and the application of Smoothed Particle Hydrodynamics (SPH) models (Heller et al., 2016; Wang et al., 2016). However, these studies still focus on simple cases and geometries rather than real-world scenarios. R.avaflow, a two-phase model that was developed to simulate debris flows into fluid bodies (Pudasaini, 2012), has been applied to simulate debris flows such as those that would be present in a GLOF (Mergili et al., 2017). Few researchers have looked at the issue of wave run-up (e.g., Synolakis, 1987 and 1991; Muller, 1995; Liu et al., 2005; Capel, 2015; Romano et al., 2015; Etemad-Shahidi et al., 2016), and most use empirical formulas or simplified approaches for wave run-up calculations, making assumptions about the lake geometry that may not be realistic (e.g., uniform water depth and a regularly sloped dam).

Although models of real events are limited by the lack of validation data, there is clearly a need to move away from simplified cases such as sliding blocks or wedges and progress towards modeling cases that more closely resemble geometries and circumstances in the field. Use of three-dimensional numerical modeling can improve simulations of avalanche-generated waves by avoiding some of the weaknesses of two-dimensional shallow water models. Some of the problems of modeling avalanche-generated impulse waves include: uncertainty in the make-up of the avalanche material (e.g., ratio of snow, ice and rock; density; viscosity) and representation of the mixing and momentum transfer when the avalanche material enters the lake.

2 Methods

A three-dimensional hydrodynamic model, FLOW 3D (Flow Science, 2012), was used to simulate waves generated from avalanches entering a glacial lake and investigate the dynamics of the wave generation, propagation, run-up and moraine overtopping. Because three-dimensional models have rarely been applied to avalanche-generated waves, there is very little information on appropriate input parameters and boundary conditions. Therefore, several input parameters have been varied in this study in order to analyze the model sensitivities and gain a better understanding of the impact of user-specified inputs on model results. The sensitivity to the turbulence model and grid size used in the simulations were investigated to determine how much these aspects of the model might contribute to the overall uncertainty. Another challenge of simulating avalanche-generated waves is appropriate representation of the avalanche entering the lake. Because there is very little knowledge about how to appropriately simulate the avalanche flow and impact with the lake, two different boundary condition methods were used in this work to help facilitate analysis of the sensitivity of the overtopping discharge to the avalanche boundary conditions. Wave generation and propagation were studied to gain insights about how this type of wave behaves and what type of model is needed (2D vs 3D and hydrostatic vs. non-hydrostatic) to accurately reproduce avalanche-generated waves of the magnitude typically seen in GLOFs.

A three-dimensional, non-hydrostatic model was chosen to give as realistic a simulation environment as possible. Although two-dimensional SWE models have been applied to simulations of avalanche-generated impulse waves (e.g., Heinrich, 1992; Zweifel et al. 2007), the size and characteristics of the waves indicate that a three-dimensional model may be more appropriate because of highly variable water depths, wave heights and vertical accelerations. Additional motivation for

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employing this model is the variable lakebed geometries of many glacial lakes that tend to have sharp discontinuities near their terminal moraines that could significantly affect wave propagation and run-up (e.g., Lake Palcacocha, as seen in Fig. 2). The lakebed topography in the FLOW 3D model was taken from a 2009 bathymetric survey (UGRH, 2009), and the topographic model that was used is a 5 x 5 m resolution DEM from airborne LIDAR and stereo images (Horizons, 2013). Three avalanche scenarios that represent a range of likely avalanche sizes were simulated in addition to two lake-lowering scenarios to evaluate hazard mitigation alternatives. The discharge hydrographs resulting from the overtopping waves were the inputs for a debris flow model used to determine the potential impact for the city of Huaraz (Somos-Valenzuela et al., 2016).

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2.1 Sensitivity Analysis: Turbulence Model and Grid Size

2.1.1 Sensitivity to Turbulence Model

The FLOW 3D simulations used a three-dimensional, non-hydrostatic numerical scheme and a re-normalization group (RNG) turbulence model with a dynamically computed mixing length; although, several other turbulence models were also tested. Very little information exists regarding the effect of turbulence models on the outcome of simulations of avalanche-generated waves. Therefore, the primary objective of assessing the sensitivity to the turbulence model is to determine how much the choice of turbulence model might affect overtopping discharges and how much attention should be given to this parameter in the modeling process.

Turbulence models are mathematical representations of the dissipation of energy from turbulence within the hydrodynamic model that cannot be represented in the model's discretization of the Navier-Stokes equations. There are a number of approaches to modeling turbulence that range in complexity. The simplest approach is an eddy viscosity model, a type of Reynolds Averaged Navier-Stokes (RANS) model that uses a single parameter to represent all of the dissipation of energy that occurs at the sub-grid scale. Usually this parameter is tied to a length scale that describes the flow such as depth or wave height. More complex RANS models can use multiple parameters to describe the turbulence (e.g., two-equation models) or vary the length scale within a simulation based on the local flow conditions (i.e. models that use dynamically-computed mixing lengths). The ability to have a variable length scale that is calculated by the model is useful when an appropriate length scale is unknown, as is the case with the type of avalanche-generated wave studied in this paper due to the rapidly changing characteristics of the flow. Large Eddy Simulation (LES) is a different approach to modeling turbulence from the RANS models. LES simulates the largest scales of turbulence within the hydrodynamic model and uses a filter to remove the smaller scales, which are accounted for within the turbulence model. The filter size is linked to the model grid size, and additional numerical errors can be introduced due to the filter width. LES models may be viewed as a middle ground between RANS models and direct numerical simulations (DNS) that solve the Navier-Stokes equations directly for all scales of turbulent flow (Ferziger and Peric, 2002).

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In this work, the RNG-dynamic mixing length model was chosen as the baseline turbulence model because an appropriate mixing length was unknown due to the highly variable nature of the flow, both spatially and temporally. The sensitivity of the simulations to the turbulence model was tested by running repeat simulations for seven different turbulence models in FLOW 3D, including: (1) RNG-dynamic mixing length (baseline model), (2) RNG-constant mixing length, (3) k-epsilon, (4) Prandtl mixing length, (5) one-equation-constant mixing length, (6) large eddy simulation (LES), and (7) laminar flow. Simulations of models (2) – (7) were compared to the baseline model for a large avalanche ($3x10^6$ m^3) at the current lake level using the percent difference in maximum wave height, peak overtopping flow rate, and total overtopping volume. Additionally, the root-mean-square deviation (RMSD) between the results of the baseline and the other models was calculated at each time step for the outflow hydrographs and the flow depth at each point within the lake.

Turbulence models (1) – (5) are Reynolds-averaged Navier-Stokes (RANS) eddy viscosity models (Pope, 2000). Model (2) is a variant of model (1) except that it uses a constant mixing length (Yakhot and Orszag, 1986). Model (3) is a two-equation model that uses several standard constants. Models (4) and (5) are the simplest eddy viscosity models used. In FLOW 3D, the constant mixing length defined in models (2) and (5) is a maximum length scale that limits the dissipation of energy, ensuring that dissipation in the models is not underrepresented (Isfahani and Brethour, 2009).

Models (6) and (7) function differently from the RANS eddy viscosity models. The accuracy of the LES model, model (6), depends on knowledge of the flow conditions so that the filter scale can be defined to allow for most of the large-scale turbulence to be resolved within the model itself rather than in the sub-grid representation of the small-scale turbulence (Pope, 2000). The results from model (6) should be viewed considering these limitations, since the grid size was not determined according to the scale of turbulence that should be resolved in the model. Model (7) ignores turbulence and simulates the flow as entirely laminar. As turbulence tends to dissipate energy, this model will under-represent dissipation.

2.1.2 Sensitivity to Grid Size

Model results tend to improve with grid refinement. The grid cell size used for the simulations was selected to allow for sufficient resolution of the topographic and bathymetric features of the glacial lake as well as the dynamic wave features during the wave generation and overtopping phases while also balancing time and computational resources. To assess the impact of grid size on model results, a simulation was run with a coarser grid.

The regular mesh used in the FLOW 3D model consists of 6 m x 5.33 m x 6.5 m grid cells in the x-, y- and z-directions, respectively, spanning distances of 2400 m (x-direction), 800 m (y-direction), and 650 m (z-direction). For the grid size sensitivity analysis, a coarse grid simulation, with double the original cell grid size, was run for the large avalanche source scenario at the current lake level.

For the coarse grid simulations, the same value for water depth at each time step in the coarse grid was assigned to the four smaller cells that fall within each cell in the coarser grid to allow for direct comparison between the results of the coarse grid simulation and the regular mesh. To compare the coarse grid results to the results from the regular model mesh, the root-mean-square error (RMSE) of fluid depth for all grid cells within the lake was calculated at each time step. Additionally, the

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2.2 Boundary Conditions: Representing Avalanche Impact

The problem of reproducing an avalanche-generated impulse wave in a hydrodynamic model of a glacial lake presents a challenge because of the complicated dynamics of mixing and dissipation of energy that occur at the point of impact; these processes are difficult to represent correctly in the model. The results of avalanche simulations performed in the Rapid Mass Movements (RAMMS) model (Christen et al., 2010; Bartelt et al., 2013), reported in Somos-Valenzuela et al. (2016), were used to generate inputs to the lake model. Two different methods of representing the impact of the avalanche with the lake and the corresponding mass and momentum transfer were tested to determine the sensitivity of the lake model to the boundary conditions. The variability in the results between the two boundary condition methods gives an approximation of the uncertainty associated with the avalanche impact and wave generation.

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2.2.1 Avalanche Source

The avalanche source boundary condition method represents the avalanche entering the lake by simulating water flowing from the lower glacier slopes into the lake. The density of the avalanche material that is typical for this type of GLOF, the mixture of snow, rock and ice, is nearly the density of water (Schneider et al., 2014); therefore, water was used in place of the avalanche fluid, and the volume of the water that represents the avalanche was the same as the total avalanche volume. This is the same approach used by Worni et al. (2014) and Fah (2005). The two fluids (water and the avalanche material) have different viscosities, but the model was adjusted to account for the effects of the lower viscosity of water (less dissipation of energy as it flows towards the lake). The depths and velocities of the avalanche entering the lake from the RAMMS model lake were matched in the FLOW 3D model by varying the height at which the initial avalanche fluid volume was released above the lake and the initial depth of the avalanche fluid in the FLOW 3D model. The momentum transfer from the avalanche to the lake is what generates the displacement wave. Thus, the wave characteristics depend both on the mass (equivalent to depth) and velocity of the avalanche as it enters the lake. If the mass and momentum of the flow representing the avalanche impacting the lake are similar in the FLOW 3D avalanche source model and RAMMS, then the FLOW 3D simulations should realistically represent the wave generation. Reflected waves may be somewhat different due to the potential settling of the avalanche material that cannot be represented in the FLOW 3D model, but these differences are probably minimal because the magnitude of the reflected wave is much less than the initial wave.

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2.2.1 Mass-momentum Source

The second boundary condition method for representing an avalanche impacting the lake was a mass-momentum source. For this method, hydrographs were constructed from the RAMMS avalanche simulations approximating the volumetric flow rate of the avalanche entering the lake by taking the depth and velocity from RAMMS at various points (approximately 10-15 points) along the edge of the lake for each time step. The average avalanche depth, velocity, and flow rate were calculated for each time step. These avalanche hydrographs were slightly altered so that the total volume was equivalent to the avalanche volume, and the resulting adjusted hydrographs were used as the inflow boundary condition of the FLOW 3D model, representing the input of mass and momentum that generates the impulse wave. This was done using the mass-momentum source function in FLOW 3D with the boundary condition defined by the hydrograph and cross-sectional area of the flow entering the lake.

2.3 Wave Characteristics

There are five main phases of an avalanche-generated impulse wave in a glacial lake: (1) wave generation from the avalanche entering the lake, (2) propagation of the wave across the lake, (3) run-up on the damming-moraine, (4) overtopping of the moraine, and (5) reflected wave(s) from the portion of the wave that does not overtop the moraine. The characterization of these phases of an avalanche-generated wave is important because empirical methods (e.g., Heller and Hager, 2010) have been developed to model wave generation, but wave propagation often cannot be accurately described by simple empirical equations, especially for glacial lakes with varying bathymetry. Wave generation is dependent primarily on the avalanche characteristics and the lake depth at the point of impact; whereas, wave propagation is dependent on initial wave characteristics, lake bathymetry and the surrounding topography.

The primary parameters used to study the wave characteristics were the maximum height of the wave in the lake and the wave height as it overtopped the moraine dam. The maximum wave height, as a function of distance along the lake, was calculated to assess how the wave changes during the propagation phase and to allow for comparison with the empirical method of Heller and Hager (2010). At this point, the difficulty of model validation and uncertainty quantification must be mentioned. In this work, events are modeled that have not yet occurred, and very little data are available from similar past events that can be used to calibrate or validate model results. There was a landslide at Lake Palcacocha in 2003 that overtopped the lake-damming moraine and caused some damage to the structure of the moraine complex. The approximate volume of this landslide is known, and the wave height was estimated to be 8 m based on the fact that moraine overtopping occurred (Vilimek et al., 2005). However, it is possible that the actual wave height in the lake was less than the estimated value because the wave height generally increases during run-up on the damming moraine. The information available for the 2003 landslide is insufficient for validation of this lake model. Similarly, the 2010 GLOF that occurred at Lake 513 in the Cordillera Blanca of Peru provides some information to compare results to, but that event occurred at a lake with unique characteristics (solid rock damming-moraine) and there is some discrepancy among the estimates of the avalanche magnitude, wave height and overtopping volume (Carey et al., 2012; Valderrama and Vilca, 2012; Schneider et al., 2014). Therefore, the results of the empirical model (Heller and Hager, 2010) were used to compare with the FLOW 3D hydrodynamic lake modeling.

The empirical method of Heller and Hager (2010) for calculating characteristics of impulse waves is based on a database of field measurements and laboratory experiments. If the characteristics of the impulse wave in both the hydrodynamic and

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empirical models are similar, then there is reason for confidence in the hydrodynamic model results. However, the empirical method is only an approximation based on simplified representations of lake geometry and avalanche characteristics. The method has certain acceptable ranges of variables, such as relative slide density, volume, width, and Froude number, for which the empirical equations hold true. For Lake Palcacocha, all the variables fall within the acceptable ranges except the relative slide width; therefore, the wave characteristics calculated according to this method can be reasonably relied upon to compare with the three-dimensional simulation results, but only to get an idea of the approximate wave dimensions.

2.4 Scenarios

Two sets of scenarios were simulated with the hydrodynamic model: avalanche scenarios and lake-lowering scenarios. To assess the current GLOF hazard, simulations were first run with the current lake level (the baseline level). The baseline level was defined as the lake level controlled by the current outlet works, a tunnel that maintains a freeboard level of 8 m and a water surface elevation of 4562 m. Three avalanche scenarios were used to represent a range of potential avalanche sizes that might impact the lake: small ($0.5x10^6$ m^3), medium ($1x10^6$ m^3) and large ($3x10^6$ m^3). The avalanche characteristics for each scenario are given in Somos-Valenzuela et al. (2016). Second, scenarios with different lake levels were simulated to study how lowering the lake surface might influence the overtopping wave volume and discharge. These scenarios included lowering the lake level 15 m and 30 m from the baseline lake level and were selected based on what has been proposed by local government technical specialists in Huaraz as plausible lake risk mitigation strategies.

Each lake level scenario (including the baseline) was simulated for all three avalanche scenarios, forming a total of 9 scenarios; the overtopping volume and outflow hydrograph were computed for each scenario. Lake lowering scenarios were analyzed for reduction in peak overtopping flow rate and total discharge volume. Although the goal of this work is examining lake hydrodynamics, the greater aim is to assess the potential for GLOFs to impact downstream populations. Simulations of downstream inundation and flood intensities can facilitate analysis of lake lowering schemes to reduce GLOF hazard levels. Somos-Valenzuela et al. (2016) evaluated how lake lowering may alter the GLOF impacts in Huaraz for the avalanche source scenarios and found that overtopping volumes of 20,000 m^3 or less would not result in significant flooding in Huaraz. Considering this, three classifications were used to describe the overtopping results for each scenario and their potential downstream impacts: (a) no discharge, (b) medium discharge ≤ $20x10^3$ m^3, (c) and high discharge > $20x10^3$ m^3. Classification (a) implies that there should not be any downstream impacts. For scenarios resulting in medium discharge, classification (b), the downstream impacts should be minimal, and scenarios resulting in high overtopping discharges, classification (c), there could be significant downstream impacts. However, these classifications should be considered in light of the significant uncertainty in the overtopping estimates. A comprehensive probabilistic hazard assessment and evaluation of mitigation alternatives is beyond the scope of this work, and these classifications of the magnitude of overtopping discharges are only intended to provide a useful tool that can be used in the decision-making process.

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Comment [RC5]: This was modified and elaborated on in response to the comment from Reviewer 2:
The crisp values listed in Table 2 and 3, and classification of scenarios into "safe" and "not safe" appear at odds with a probabilistic assessment but should rather incorporate uncertainty characterization which could either be quantitative (Table 2,3) or qualitative (Table 4) and derived from the sensitivity analysis.

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3 Results

For each scenario, FLOW 3D was used to model the avalanche-generated impulse wave, from the wave generation to the overtopping phases. For each avalanche event, simulations were run using both boundary condition methods (avalanche and mass-momentum sources), first for the baseline lake level and then for the two lake-lowering scenarios.

3.1 Sensitivity Analysis: Turbulence Model and Grid Size

3.1.1 Sensitivity to Turbulence Model

For the large size scenario with the avalanche-source boundary condition and current lake level, the results of using the various turbulence models were compared to the baseline model (1) (RNG-dynamic mixing length). The RMSD (Fig. 3) shows the average difference in fluid depth between the baseline model and each of the other turbulence models. For all models, the highest RMSD values were for times up to 50 s when the water surface is most actively changing as the impulse wave is generated and begins to propagate across the lake. Models (6) (LES) and (7) (laminar) show the most deviation from the baseline model with maximum RMSD values around 2.5 m. The laminar model shows high deviations from the baseline model because it does not account for turbulence and should be the least dissipative of all the models. This is reflected in the peak flow rate, overtopping volume and maximum wave height (Table 1), which were all higher than the baseline model. The LES model appears to be overly dissipative, giving the lowest values for all parameters used for comparison between the models. It is difficult to say why this is the case, but it could be due to inhomogeneity in the flow or numerical errors due to the filter scale.

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Models (2) (RNG-constant mixing length), (3) (k-epsilon) and (4) (Prandtl mixing length) may be more appropriate for this type of simulation. The results from these models more closely align with the baseline model; however, there are still differences in fluid depth between the models. All three models had maximum RMSD values for fluid depth of around 1.8 m; the models approached a steady state (RMSD of approximately 0.5 m) after 200 s when the initial wave overtopped the moraine. The highly variable lake bathymetry and fluid depths make defining an appropriate mixing length difficult and introduce a source of uncertainty in the model; many of the turbulence models require the definition of a mixing length that ensures that the dissipation of energy is not underrepresented in the model. For this reason, model (1) appears to be the optimal choice in this case. Yet, the similarity in the results between the RANS eddy viscosity models (1) – (5) indicates that the uncertainty introduced by the constant mixing length models is relatively insignificant.

The RMSD of the overtopping hydrograph flow rates for each of the turbulence models are given in Table 1 along with additional comparisons of the hydrographs, including the percent difference in peak flow rate and total overtopping volume. The largest differences in flow rate and overtopping volume came from models (6) (LES) and (7) (laminar) with the laminar model producing higher flows and the LES model producing the lowest flow rates. The hydrographs from the other models resembled that of the baseline model. The percent differences in peak flow rate from the eddy viscosity models ranged from around 0.25% for model (4) (Prandtl) to around 3% for model (3) (k-epsilon). The differences in total overtopping volume were a little higher, although all were less than 5%, and the differences in maximum wave height were much less significant for all but model (6) (LES), with most models giving differences less than 2%.

The laminar model (7) is the only model that gave higher flow rates and overtopping volumes than the baseline model, indicating that even if the turbulence model introduces uncertainty into the model results, the results of the baseline model are most likely conservative, giving possibly higher discharges. Considering all the other sources of uncertainty in the models of the avalanche and wave generation, the turbulence model is one of the less significant sources of uncertainty.

3.1.2 Sensitivity to Grid Size

The RMSE of fluid depth for the coarse grid simulation compared to the regular mesh is a good measure of the error introduced by changing the grid resolution (Fig. 4). The highest errors were in the first 50 s of the simulation time, during the wave generation, propagation and run-up phases. However, there was a baseline level of error that comes simply from extrapolating the initial conditions to a coarser grid because the bathymetry and initial fluid depths are better represented in the fine grid model; this baseline error was unavoidable because the resolution of the bathymetry must be the same as the resolution of the model grid, so we lose some of the precision of the bathymetric representation in the model with the coarse grid. The RMSE at t = 0 reflects this error. After 50 s, the RMSE began to level off at a relatively consistent level of approximately 1.5 m. This was about three times higher than the RMSD from the eddy viscosity turbulence models at the same point in time, indicating that grid size could introduce much more error than the turbulence model.

The RMSE of overtopping discharge for the coarse grid simulation was approximately 3300 m^3/s. This amount of error is not insignificant; it is approximately three times the RMSD for the eddy viscosity turbulence models but less than the RMSD for the laminar flow model. The peak discharge from the coarse grid simulation was over 5% higher than the peak discharge from the regular grid size model (a difference of 4,200 m^3/s). The total overtopping volume was slightly higher for the coarse grid simulation (a difference of 30,000 m^3), but the difference was less than 1%, so the coarse grid model seems to estimate the total overtopping volume well even if it does not get the wave dynamics and outflow hydrograph completely correct. Although the error resulting from using a coarser mesh was greater than the uncertainty from most of the turbulence models, the uncertainty due to the grid size is still not a very large source of error.

3.2 Comparison of Boundary Conditions: Avalanche Source vs. Mass-momentum Source

The inflow hydrographs of the two boundary condition methods are shown in Fig. 5 along with the hydrograph from the RAMMS avalanche model (Somos-Valenzuela et al., 2016). For all three avalanche scenarios, the peak inflow for the avalanche source was significantly higher than for the mass-momentum source. The mass-momentum boundary condition inflows were very close to those of the RAMMS model in each case because the boundary condition was defined to match the RAMMS avalanche hydrograph. The higher peak inflows for the avalanche boundary condition are probably because the lower viscosity of water relative to the avalanche material allows the fluid to flow and spread out more quickly; to compensate for this, the avalanche boundary condition fluid release volume was concentrated over a smaller area so that the fluid depths would not be too low, but the result was higher inflow rates over a shorter period. The peak inflow rates for the avalanche boundary condition ranged from nearly twice the peak flow rate of the RAMMS avalanche for the large scenario to over 5 times higher for the small scenario, but the inflows for the avalanche boundary condition were of much shorter duration. For the large scenario, peak overtopping discharge for the mass-momentum boundary condition (Table 2) was 14% less than the discharge for the avalanche boundary condition (compared to a difference of about 50% for the inflows). However, for the medium and small scenarios, the difference in peak overtopping discharge between the two boundary condition models was more pronounced. For the medium mass-momentum boundary condition, the overtopping discharge was 65% less than the discharge from the medium avalanche boundary condition; this difference was only slightly lower than the difference in peak inflow (~75%). The overtopping discharge for the small mass-momentum boundary condition was almost 91% less than the discharge for the small avalanche boundary condition (with difference in peak inflow of around 80%). While the difference in overtopping volumes for the *large* avalanche and mass-momentum boundary condition was only 9%, the total overtopping volume for the *small* mass-momentum boundary condition was over an order of magnitude less than the overtopping volume resulting from the small avalanche boundary condition (Table 2).

There were a few irregularities in the inflow hydrographs that should be mentioned. First, the large avalanche source inflow hydrograph had a bimodal peak, likely due to the way in which the initial avalanche fluid volume was defined. The initial fluid volume was defined as blocks of water above the natural terrain, the surface elevations of which were set at graduated levels, taking the shape of steps to more closely mimic the natural descent of the terrain and have a relatively constant initial water depth; this definition of the initial fluid release volume is not realistic, but after it was released, the fluid flowed into a more natural state. However, for the large avalanche source, the sections of the initial fluid volume most likely had variations in the initial water surface elevation that were too abrupt so that the fluid did not coalesce into one continuous surface but rather had two areas of peak flow depth. This is a problem that results from releasing blocks of water just above the lake; the initial fluid volume is not realistic, but water will even out into a natural flow before it reaches the lake. The fluid cannot be released at a point that is too high or the velocities will be excessive, but to get a high enough volume with accurate depths, it is difficult to get an even flow by the time the water reaches the lake. A second irregularity was the smaller, second peak in the inflow hydrographs from the avalanche boundary condition in the medium and small scenarios, likely the result of flow entering the lake from the sides. This is not unrealistic, since there was inflow from the sides of the lake in the avalanche model. However, due to the higher viscosity of the snow-rock-ice mixture of the avalanche, the inflow from the lateral moraines probably would happen more gradually so that the abrupt inflow from the sides would not cause such a significant peak in the inflow hydrograph.

3.3 Wave Characteristics

The impact of the avalanche with the lake generates a large displacement wave. As the wave propagates across the lake, it reaches a maximum height as it approaches the shallow part of the lake near the damming-moraine (Fig. 6). The characteristics of the waves generated for each avalanche scenario are given in Table 3. The FLOW 3D wave heights were

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all larger than the empirically-calculated wave heights (Heller and Hager, 2010); however, the waves were of a similar magnitude with both methods with a difference in maximum wave height between FLOW 3D and the empirical method of 14% (5.8 m) for the large avalanche source. The FLOW 3D results showed attenuation of the wave as it propagated along the lake; this attenuation resulted in a reduction in the wave height of approximately 30% before the wave began the run-up phase (Fig. 6).

Upon closer examination, the wave generated from the large avalanche source (Fig. 6) had two peaks that were of similar height. The first peak was near the avalanche impact, corresponding to the location of the wave represented by the empirical equations; the second peak, that was slightly higher, occurred as the wave began to run up on the shallower part of the lake. The wave characteristics calculated by the empirical method consider the wave generation process but do not account for the impact of run-up on the wave characteristics. Therefore, the peak wave height in the deeper portion of the lake is the closest point of comparison with the empirical equations. Fig. 6 gives the wave height as a function of distance along the lake (not as a function of time); there were some oscillations in the profile of the maximum wave height, most likely due to splashing from the run-up on the sides that was reflected off the lateral moraines and returned to the lake at irregular intervals.

3.4 Overtopping Hydrographs and Volumes

The run-up phase culminates with the moraine overtopping; the wave heights given in Table 2 correspond to the height above the moraine crest as the wave overtops the damming-moraine. The volume of water that resulted from the overtopping of the moraine was significant; the total overtopping discharge volume for each scenario is given in Table 2, and the overtopping hydrographs are shown in Fig. 7. The large avalanche source resulted in a peak overtopping discharge of approximately 63,000 m^3/s that occurred around 60 s after the start of the avalanche as well as a smaller peak of 6,000 m^3/s resulting from the overtopping of the reflected wave. The overtopping of the initial wave lasted about 100 seconds for the large avalanche source, 70 seconds for the medium avalanche source, and 50 seconds for the small avalanche source.

The mass-momentum boundary condition consistently resulted in lower overtopping discharges and volumes, but the differences between the mass-momentum and avalanche boundary condition were more pronounced for the small and medium scenarios. For the large mass-momentum boundary condition, the peak overtopping flow rate was 14% less than that of the avalanche boundary condition. The large mass-momentum boundary condition overtopping volume was 11% less than the avalanche boundary condition overtopping volume. For the medium mass-momentum boundary condition, the peak discharge and overtopping volume were 65% and 70% less than the avalanche boundary condition, respectively, and the difference in both the peak discharge and overtopping volume between the small avalanche and mass-momentum boundary conditions was 91%.

The overtopping volumes for all scenarios were less than the volume of avalanche material entering the lake. The overtopping volume for the large avalanche boundary condition was 60% of the avalanche volume, and for the medium and small avalanche boundary conditions, the overtopping volumes were 50% and 30% of the avalanche volumes respectively.

The overtopping volume decreases relative to the avalanche volume as the avalanche size decreases, indicating that the lake has more capacity to dissipate smaller avalanche-generated waves.

3.5 Lake Lowering Scenarios

Two scenarios of lake lowering were simulated to evaluate the potential effect of lowering the lake level as a mitigation strategy. Three avalanche sizes and both types of boundary conditions were simulated with each lake level, resulting in a total of 18 simulations. The overtopping volumes and peak discharges were somewhat reduced by lowering the lake 15 m, while 30 m lowering resulted in even further reductions in overtopping discharges (Table 2). The hydrographs for the overtopping discharge are shown in Fig. 8.

Lowering the lake level, even by as much as 30 m, did not completely prevent overtopping of the damming-moraine. Nonetheless, overtopping may be prevented by lake lowering for smaller avalanches. A 90% reduction of overtopping volume may be achieved for the medium avalanche boundary condition through lowering the lake level by 30 m. Overtopping was not avoided entirely with the 15 m lake lowering, but the overtopping volumes and discharges were approximately 60% and 80% less than with the current lake level for the medium and small avalanches, respectively. Lake lowering appears to have the least impact for large avalanches, as significant overtopping still occurred under all lake lowering scenarios for a large avalanche. However, the overtopping volume was reduced by 28% for the large avalanche boundary condition, with 30 m lake lowering and by 73% for the large mass-momentum boundary condition, with 30 m lake lowering. The categorization of each scenario according to the overtopping volume (Sect. 2.4) is given in Table 4.

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The overtopping wave heights increased with lake lowering even though the total overtopping volumes and peak flow rates decreased. This may seem counterintuitive, but it can be explained by looking at how the lake dynamics may be expected to change with lake lowering. First, as the water surface level is lowered, the total volume stored in the lake increases, thus the momentum transferred to the lake from the avalanches per unit volume should be higher. The total volume in the lake decreases with lake lowering, so the additional momentum relative to the lake volume can produce taller waves. Secondly, as the point of avalanche impact is at a lower elevation relative to the avalanche release area with lake-lowering, there is more momentum in the avalanche fluid when it enters the lake. Although the increased overtopping wave heights for the lake lowering scenarios indicate that the waves may be larger when the lake is lowered, the amount of overtopping still decreases with lake lowering. This is most likely due to the lower initial water surface elevation; the lower free surface elevation results in a larger freeboard and means that more momentum is required for overtopping; although the momentum transfer per unit volume to the lake from the avalanche is greater, more of this momentum is lost during the run-up and overtopping, and less water is actually able to pass over the crest of the terminal moraine.

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4 Discussion

4.1 Boundary Condition Methods

Although the avalanche boundary condition seems to have more uncertainty than the mass-momentum boundary condition, each boundary condition method has its limitations. The complex nature of the interacting dynamic physical systems makes it difficult to develop a comprehensive and precise method for simulating avalanche-generated waves in glacial lakes. Recent advances in two-phase flow models such as r.avaflow (Pudasaini, 2012; Mergili, 2017) can facilitate simulations of wave generation from avalanches entering a lake; however, the use of depth-averaged equations still limits the ability to use this type of model to simulate all of the phases of an avalanche-generated wave from wave generation to overtopping. Avalanches typically consist of a mixture of snow, ice and rock, and the biggest limitation of the boundary conditions in this model is the representation of the avalanche fluid as water because the dissipation of energy of the actual avalanche material is different from water. This limitation can be partially overcome by calibrating the model to replicate the depth and velocity characteristics of the avalanche as it enters the lake. This is done by adjusting the avalanche release area in the avalanche boundary condition and the hydrograph and cross-sectional area of the inflow for the mass-momentum boundary condition. However, it is impossible to completely replicate the avalanche characteristics in the lake hydrodynamic model, and there are significant differences in the inflow hydrographs of the FLOW 3D model and the RAMMS avalanche model (like the mass-momentum source) when the avalanche boundary condition is used. The discrepancies between the avalanche and mass-momentum boundary conditions are more pronounced for smaller avalanches, but there is no obvious solution to overcome this difficulty when using the avalanche boundary condition. To further advance the simulation of avalanche-generated waves, models are needed that can easily and accurately represent two distinct fluids (in this case the mixture of snow, rock and ice of the avalanche and the water in the lake) combined with non-hydrostatic free surface flows. Without two-phase models that can simulate free surface flows, it will not be easy to overcome the limitations and irregularities of the model that result from the representation of the avalanche fluid as water.

The avalanche boundary condition has much higher and possibly unrealistic peak inflow rates, but it gives a better physical representation of the actual geometry of the terrain as the avalanche enters the lake. The avalanche boundary condition is also able to simulate the effects of avalanche material entering the sides of lake, whereas the mass-momentum boundary condition only simulates flow entering from the end of the lake. The mass-momentum boundary condition better matches the peak flow rates of the avalanche because that is how the method was designed; the flow rate of the avalanche inflow is a control parameter for the mass-momentum boundary condition. However, under this boundary condition, the avalanche material enters the lake horizontally, rather than on the steep incline of the actual terrain above the lake. Therefore, this boundary condition likely underestimates the momentum transfer between the avalanche and the lake, as the avalanche can gain more momentum as it enters the lake at a downward angle. Despite the limitations of each boundary condition method, they are representing a range of possible outcomes, and the results could be considered as upper and lower bounds on the overtopping discharge from the lake model. Because we do not have any field measurements of the characteristics of

Comment [RC6]: This section has been organized by sub-topic in response to the comment from Reviewer 1.

Moved up [4]: This paper presents three-dimensional simulations of avalanche-generated waves, one step in the GLOF chain of processes. The lake hydrodynamic model improves upon previous two-dimensional SWE simulations of avalanche-generated waves in GLOF process chain modeling that must be calibrated with data from past GLOF events (e.g., Schneider et al., 2014). Many glacial lakes that are currently dangerous have not previously outburst, so the use of data from prior GLOF events is not an option at many study sites. Additionally, GLOF modeling for hazard mapping requires predictive modeling of multiple scenarios. Because three-dimensional non-hydrostatic models represent more of the physical processes, they require less calibration and can be used for predictive modeling of lake dynamics and moraine overtopping. Thus, three-dimensional lake models may be a desirable alternative to two-dimensional SWE models for wave simulations. Despite the advantages of three-dimensional models for hydrodynamic lake simulations, these models still carry a considerable amount of uncertainty, and there is a dearth of field observations that can be used for model validation.

avalanche-generated waves during GLOF events or the resulting discharge hydrographs, we do not possess the means of validating the model results presented in this paper or conclusively evaluating the boundary condition methods.

The avalanche simulation is the process in the GLOF chain of events that carries the greatest uncertainty because avalanche dynamics may be the least understood of the processes. The range of uncertainty in the avalanche conditions (depths, flow rates and velocities) is possibly greater than the range of variability in the inflow hydrographs for the lake model. We have no estimates of the uncertainty in the avalanche model, but any uncertainties in the avalanche simulations are propagated into the lake model and subsequent processes in the GLOF chain of events. Although there is significant variability between the avalanche and mass-momentum boundary condition results, the range of variability in the peak flow and shape of the avalanche hydrographs may be even greater than the variability in the discharge hydrographs from the lake model.

4.2 Wave Characteristics

The characteristics of the wave as it propagates across the lake are significant indicators of the magnitude of the event that is being simulated. The wave heights are quite large (up to nearly 50 m tall) when compared with the initial depths of the lake that range from 72 m to less than 10 m (UGRH, 2009). Such large waves relative to the lake depths indicate that vertical accelerations are significant and should not be neglected. Thus, a non-hydrostatic model is essential for accurately representing the wave dynamics. Because the type field data that would be needed for model validation (e.g., wave characteristics such as wave height and attenuation) were not available, wave heights from the FLOW 3D simulations were compared with those calculated with the empirical equations of Heller and Hager (2010). The empirical model has been compared to measured data and laboratory experiments (a form of validation of the method), so it may reasonably be concluded that if the 3D model gives similar values for the wave characteristics, we can have more confidence in the 3D model. However, this comparison is only valid for the wave generation phase and maximum wave heights, as the empirical model does not represent the wave propagation, run-up and overtopping phases well. The FLOW 3D simulations did a reasonable job reproducing the maximum wave heights, especially for the larger avalanche scenarios. The FLOW 3D simulations also account for lake bathymetry and give a more accurate representation of the dissipation of energy during the propagation phase; thus, the FLOW 3D model can likely produce more realistic overtopping discharges than the empirical method. For the large avalanche scenario, both boundary conditions resulted in wave heights that were only 4.4-5.8 m higher than the empirically calculated wave heights. However, it is worth noting that the maximum wave height for the large avalanche boundary condition occurred at the beginning of the run-up phase in the shallow part of the lake, and the first wave peak in the deep portion of the lake was closer to the empirically predicted height. The large differences between the empirical and FLOW 3D wave heights for the medium and small scenarios may be due to the shortcomings of the avalanche boundary condition. Nevertheless, the relatively close agreement between the empirical and hydrodynamic models for the large avalanche scenario indicates that it may be possible to use the empirical method as a calibration tool.

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Comment [RC8]: This text has been modified to address the comment from Reviewer 1: P15L02-L07: comparing different models between each others with no comparison to reality seems slightly purposeless to me

During the run-up phase of the wave propagation, two things happened simultaneously. The wave height increased due to the run-up in the shallow portion of the lake, but there was also some energy loss due to the sharp discontinuity in the lakebed geometry. Generally, one might expect the wave height to increase even more than what occurred in the FLOW 3D simulations; however, due to the lakebed geometry, there is more dissipation of energy when the wave reaches the shallow portion of the lake than would occur if there were a more gradual transition between the deep and shallow areas of the lake.

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4.3 Model Sensitivities and Uncertainties

Comment [RC9]: This section has been expanded in response to the comment from Reviewer 2

When model calibration and validation with field data is impossible, it is important to understand the model sensitivity to input parameters. This sensitivity analysis may be used in lieu of validation in order to better understand the uncertainties of the model so that we do not represent more confidence in the model results than is justifiable given the uncertainties in the modeling process. The greatest uncertainty in the lake modeling arises from the wave generation and avalanche characteristics. Uncertainties due to the turbulence model and grid size are not negligible, but they are small compared to the magnitude of uncertainty from the wave generation.

The input parameter that seems to generate the least sensitivity is the turbulence model, with most variables used to evaluate the sensitivity varying less than 3%. Although the results were somewhat more sensitive when the LES model and laminar flow model were used, this may be expected because neither model would be considered an appropriate choice for this application. We have insufficient information to correctly apply the LES model, and we know that the flow is not laminar, so neglecting turbulence altogether would underrepresent the dissipation of energy in the model. The RANS turbulence models all gave similar results. Therefore, the choice of turbulence model should likely have little impact on the results of the lake model, even when input parameters such as the mixing length are unknown. Nonetheless, the turbulence models that use a dynamically computed mixing length are still probably the best choice because they eliminate the need for assumptions about the flow characteristics.

While the model sensitivity to grid size is greater than the sensitivity to the turbulence model, the variability in the analysis parameters was still generally less than 5%. In addition, the coarse grid simulation gave a larger overtopping volume and peak flow, so even though some error may be introduced by increasing the grid spacing, in this case it gave a more conservative result. However, any conclusions made from these results should be done carefully. The analysis of the effect of grid size on model results presented in this paper is not comprehensive, and it may be that further increasing the size of the grid cells could have an undesirable effect on the reliability of the model results. Nonetheless, the choice of grid size is likely to be a much less significant source of uncertainty than the boundary conditions.

One way to estimate the uncertainty in the wave generation is by using more than one method to represent the impact of the avalanche with the lake (i.e., the two methods for modeling the boundary conditions). Without any in situ data from real events, the level of uncertainty cannot be estimated precisely, but given the range of overtopping flows and volumes from the two boundary condition methods, the uncertainty is considerable. Although there is no way to validate the results to know which type of boundary condition is more representative of the actual conditions, it is possible that the avalanche boundary condition is overestimating the momentum transfer while the mass-momentum boundary condition is likely underestimating it. The avalanche boundary condition could represent an upper bound for the simulation results while the mass-momentum source may be closer to a lower bound.

The scenarios of avalanche size cover a range of possible avalanche volumes that could trigger GLOFs of significant size, and the analysis of the results from these scenarios may be considered as a measure of the sensitivity of the overtopping discharge to the input parameters related to avalanche characteristics. The avalanche characteristics carry their own uncertainties that are propagated into the lake model and subsequent downstream processes, and these uncertainties are probably much greater than the uncertainties associated with the turbulence model and grid size. Although we do not have enough information to quantify the uncertainty from the avalanche model, evaluating the potential effect of different sized avalanches on overtopping discharges can help us better understand the downstream sensitivity to the avalanche characteristics.

4.4 Implications of Model Results

This paper focuses exclusively on the lake hydrodynamics and does not consider the uncertainties in the avalanche simulations or the question of dynamic erosion of the terminal moraine due to overtopping flows. The avalanche is the portion of the GLOF process chain that is the least understood and most likely the greatest source of uncertainty in GLOF modeling and hazard mapping. Although the uncertainty resulting from the avalanche portion of the chain of events must be considered in the decision-making process, investigating the uncertainty in the avalanche characteristics is beyond the scope of this work. In a way, the avalanche scenarios are attempting to capture some of that uncertainty, but it does not represent all of the uncertainty associated with the avalanche model. This work explores the uncertainties that arise when representing the impact of the avalanche with the lake and the wave generation, but this is necessarily limited by the avalanche characteristics that were available from the avalanche simulations. Until further advances are made in the field of avalanche simulations and we gain an improved understanding of avalanche dynamics for this type of event, it is impossible to incorporate all of the uncertainty of potential avalanches into analysis of the dynamics of avalanche-generated waves. All that we can do is assess the sensitivity of the lake model to different types of inputs to gain a qualitative understanding of how these uncertainties might impact the characteristics of avalanche-generated waves and the overtopping discharges. The potential erosion of the terminal moraine is also an important factor to consider when assessing the hazard level of any glacial lake with a moraine dam. For Lake Palcacocha, this was assessed by Somos-Valenzuela et al. (2016) through a separate hydromorphodynamic model, and the conclusion was that despite significant potential for erosion, the moraine is extremely unlikely to fail.

The results from the large avalanche simulations represent the worst-case scenario of an avalanche-induced GLOF from Lake Palcacocha if the moraine is as stable as it seems. Given the significant differences between the small and medium

Comment [RC10]: This section has been revised to address Reviewer 1's comment: **P16L19: from my point of view, the greatest uncertainity arises from not knowing realistic (field investigation-based) scenarios of potential ice avalanches entering Lake Palcacocha, making all hazard mitigation implications and conclusions rather speculative; please discuss that**

avalanche simulations, results from both boundary condition methods should be provided if these scenarios and their likelihoods will be used in an economic or risk and vulnerability analysis of the mitigation alternatives. All the large avalanche scenarios and most of the medium avalanche scenarios resulted in significant overtopping, even with lake lowering. Thus, it is clear that steps to mitigate or reduce the hazard must be taken because even with the low end of the range of uncertainty in avalanche sizes, the resulting discharges could represent an unacceptable level of risk for the city of Huaraz, as was also indicated in Somos-Valenzuela et al. (2016). However, the classification of overtopping discharges by volume used here (Table 4) is not fully indicative of the effect of lake lowering on hazard mitigation. The downstream impacts for each scenario should be considered when evaluating lake lowering scenarios, but decision makers must also recognize the uncertainty contained in these GLOF hazard assessments. The potential for lake lowering works to prevent overtopping for the small and medium avalanche scenarios is significant because small and medium avalanches are believed to be much more likely than large avalanches (Huggel et al., 2004); therefore, the real impact of lake lowering may be more than is immediately apparent with these results. However, from the modeling results alone it is not possible to determine an optimum lake level. Further economic and vulnerability analyses are necessary to recommend an ideal mitigation alternative.

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5 Conclusions

Three-dimensional non-hydrostatic models can be a useful tool to simulate avalanche-generated waves and improve our understanding of lake dynamics during GLOF events. The simulations of Lake Palcacocha show that waves of considerable magnitude can be produced. While sensitivity of the overtopping discharge to the turbulence model and grid size is minimal, the avalanche characteristics and the shape of the inflow hydrographs substantially influence the overtopping wave volumes. While large avalanches produce the largest overtopping discharges, even smaller avalanches could generate significant overtopping discharges. Based on the downstream inundation analysis in Somos-Valenzuela et al. (2016), even the small avalanche scenario could result in substantial inundation in the city. Somos-Valenzuela et al. (2016) only evaluate scenarios that use the avalanche source boundary condition, but the results presented here indicate that the overtopping discharges with the mass-momentum source boundary condition may be lower than those evaluated for downstream impacts in Somos-Valenzuela et al. (2016). Based on this, it can be concluded that there is a considerable amount of uncertainty in the lake model due to the boundary condition method. However, even considering this uncertainty, we can still conclude that overtopping discharges for the current lake level could be significant. Lowering the lake level may reduce the overtopping volume and discharge for a large avalanche, but it is not possible to eliminate the potential for overtopping. For small ($0.5x10^6$ m^3) and medium ($1x10^6$ m^3) avalanches, it may be possible for the wave to be contained in the lake if the water surface is lowered. However, given the range of uncertainty in the model results, it cannot be stated conclusively that lowering the lake level would prevent overtopping for smaller avalanches. Even though the precise reduction in hazard level due to lake lowering cannot be quantified, it is reasonable to conclude that lowering the level of Lake Palcacocha can reduce the hazard levels in the city of Huaraz.

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The modeling reported here provides a significant advancement beyond previous simulations of avalanche-generated waves. Model calibration is less important for the three-dimensional modeling approach due to the improved representation of physical processes as compared with two-dimensional SWE models; therefore, it presents an alternative that can be used when field data from a prior GLOF are not available for model calibration. Despite the advantages of this method, uncertainties are still present; however, as the fundamental physical phenomena are better represented in three-dimensional models, errors can be attributed more to uncertainties in the physical parameters, initial and boundary conditions rather than the model constructs. Nonetheless, the lake dynamics still remain a problematic link in attempts to model the GLOF process chain. The sensitivity analyses presented in this paper should help future modelers understand the uncertainties associated with the modeling of displacement waves and assist them in determining which input parameters need the most attention. Given the considerable sensitivity of the lake model to the boundary condition method (representation of the impact of the avalanche with the lake), it is recommended that more than one boundary condition method be used. Until we gain a better understanding of the dynamics of mass movements and their influence on wave generation, it is best to consider a range of possible outcomes rather than selecting just one method and assuming that it accurately depicts the wave characteristics. Avalanche simulation is the GLOF process chain link that carries the greatest uncertainty, and much of that is propagated into the lake model. Precise knowledge of avalanche behavior is limited, and so it is difficult to evaluate how well the lake model represents the avalanche as it enters the lake. Because the lake model is so heavily influenced by the avalanche characteristics, it is hard to quantify the uncertainty in the wave simulations. More studies are needed to gain a better understanding of the magnitudes and sources of uncertainty in glacial lake modeling of waves generated by mass movements.

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Competing Interests

The authors declare that they have no conflict of interest.

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Table 1. Comparison of overtopping hydrograph characteristics among turbulence models.

#	Model	RMSD (m^3/s)	Difference in Peak Flow Rate		Difference in Overtopping Volume		Difference in Maximum Wave Height	
			m^3/s	%	10^6 m^3	%	m	%
2	RNG-Constant Mixing Length	1,188	-1,100	-1.40	-0.08	-3.60	-0.09	-0.17
3	k-epsilon	726	-2,400	-3.05	-0.11	-4.80	-0.71	-1.38
4	Prandtl Mixing Length	816	-200	-0.25	-0.09	-3.91	0.43	0.83
5	One-Equation-Constant Mixing Length	1,190	-700	-0.89	-0.09	-4.02	0.42	0.80
6	LES	3,047	-6,600	-8.39	-0.25	-10.4	-1.9	-3.64
7	Laminar	3,386	5,200	6.61	0.09	3.60	0.81	1.57

Table 2. Overtopping characteristics of three simulated avalanche events of different size for the current lake level and lake lowering scenarios (after Somos-Valenzuela et al., 2016).

Lake lowering	Boundary condition	Overtopping	Avalanche size		
			Large	Medium	Small
Baseline (0 m lower)	Avalanche	Volume (10^6 m^3)	1.80	0.50	0.15
		Peak discharge (m^3/s)	63,400	17,100	6,410
		Wave height (m)	21.7	12.0	7.1
	Mass-momentum	Volume (10^6 m^3)	1.64	0.15	0.014
		Peak discharge (m^3/s)	54,600	6,000	592
		Wave height (m)	15.9	-	-
15 m lower	Avalanche	Volume (10^6 m^3)	1.60	0.20	0.02
		Peak discharge (m^3/s)	60,200	6,370	1,080
		Wave height (m)	38.4	27.5	25.1
	Mass-momentum	Volume (10^6 m^3)	0.83	0.034	0
		Peak discharge (m^3/s)	25,700	1,510	0
		Wave height (m)	32.0	25.4	0
30 m lower	Avalanche	Volume (10^6 m^3)	1.30	0.05	0
		Peak discharge (m^3/s)	48,500	1,840	0
		Wave height (m)	60.8	42.5	0
	Mass-momentum	Volume (10^6 m^3)	0.45	0	0
		Peak discharge (m^3/s)	15,100	0	0
		Wave height (m)	46.1	0	0

Table 3. Comparison of maximum wave heights for FLOW 3D and empirical calculations.

Avalanche size	Boundary condition	Max. wave height (m)		Distance to peak (m)
		Empirical	FLOW 3D	FLOW 3D
Large	Avalanche	42	47.8	1080
	Mass-Momentum		46.4	1039
Medium	Avalanche	21	30.1	318
	Mass-Momentum		NA	NA
Small	Avalanche	9	19.6	108
	Mass-Momentum		NA	NA

Table 4. Characterization of scenario according to the volume of overtopping discharge. Scenarios labeled as "High discharge" had overtopping volumes > 20 x 10^3 m^3. Scenarios labeled as "Medium discharge" had overtopping volumes ≤ 20 x 10^3 m^3. Scenarios labeled as "No discharge" did not result in any overtopping.

Avalanche size	Boundary condition	Lake-lowering 0 m	Lake-lowering 15 m	Lake-lowering 30 m
Large	Avalanche	High discharge	High discharge	High discharge
	Mass-momentum	High discharge	High discharge	High discharge
Medium	Avalanche	High discharge	High discharge	High discharge
	Mass-momentum	High discharge	Medium discharge	No discharge
Small	Avalanche	High discharge	Medium discharge	No discharge
	Mass-momentum	Medium discharge	No discharge	No discharge

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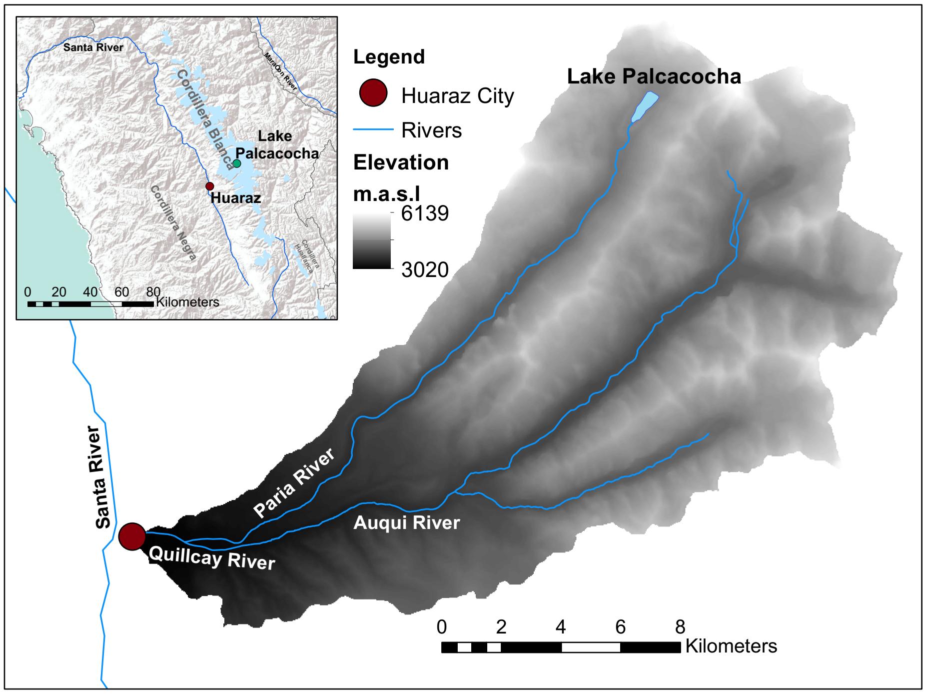

Figure 1: Location of Lake Palcacocha within the Cordillera Blanca, Peru.

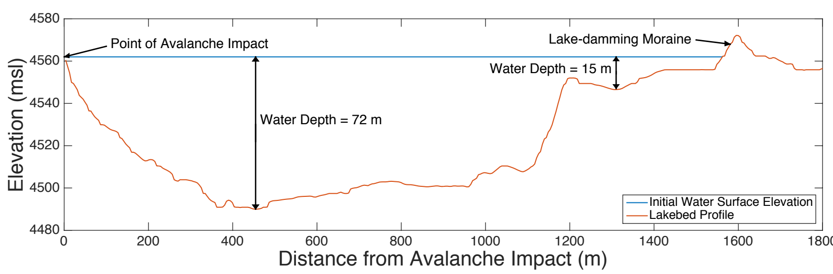

Figure 2. Longitudinal profile of Lake Palcacocha and its terminal moraine.

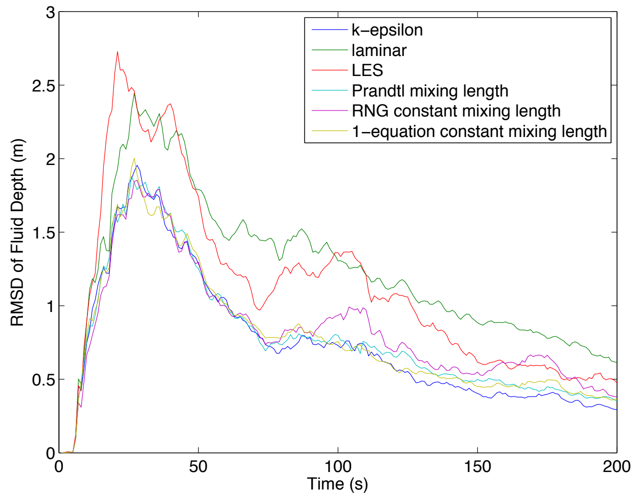

Figure 3. Root-mean-square deviation (RMSD) of fluid depth from the baseline model results (RNG-dynamically computed mixing length) for each turbulence model as a function of time.

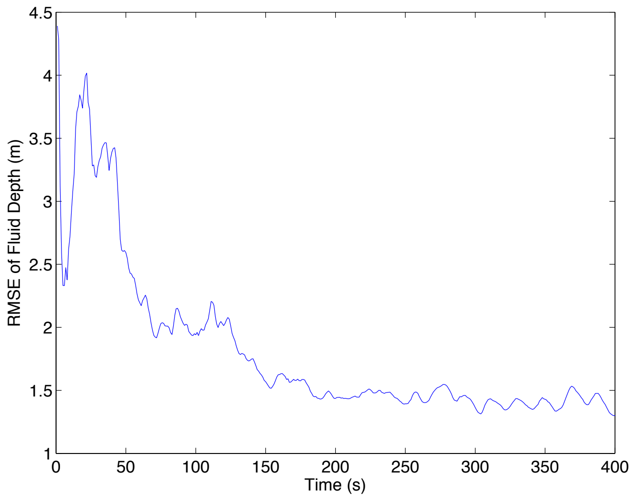

Figure 4. RMSE of fluid depth for the coarse grid simulation as compared to the regular grid mesh using the baseline turbulence model.

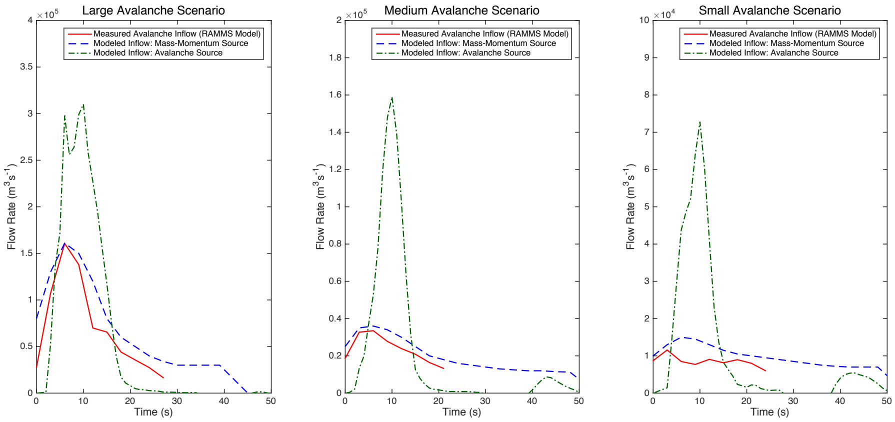

Figure 5. Inflow hydrographs for the avalanche as it enters the lake for the avalanche source and mass-momentum source boundary conditions as compared to the hydrograph extracted from the RAMMS avalanche model.

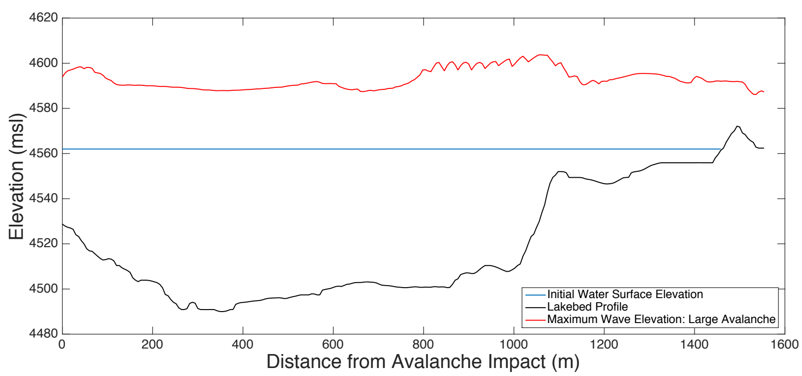

Figure 6. Profile of the maximum wave height as a function of distance along the lake for the large avalanche boundary condition.

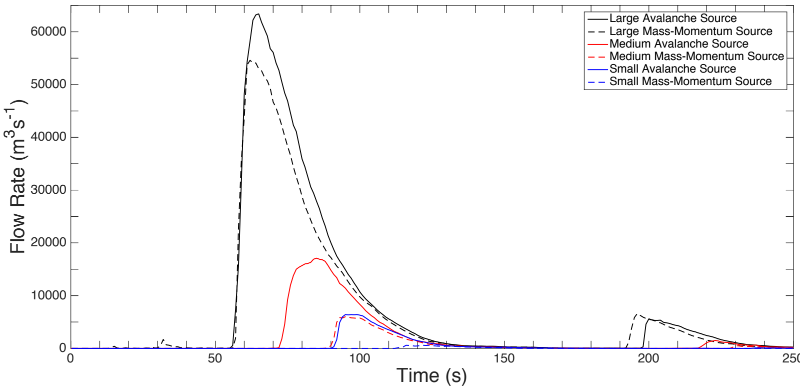

Figure 7. Overtopping wave discharge hydrographs for the three avalanche events and two types of boundary conditions with the lake at the baseline level.

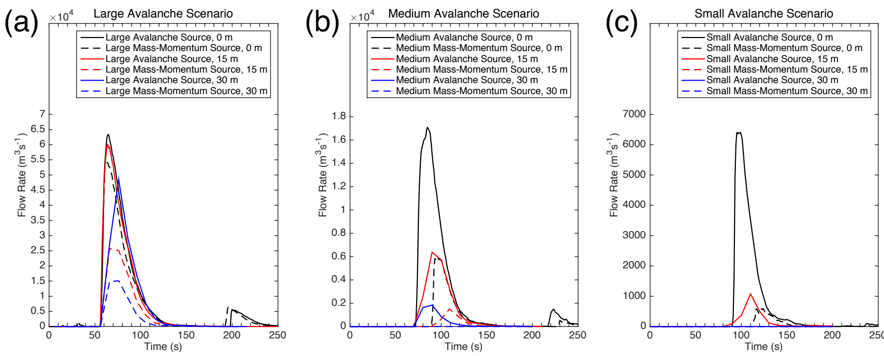

Figure 8. Overtopping hydrographs for lake lowering scenarios for (a) large avalanche scenario, (b) medium avalanche scenario, and (c) small avalanche scenario.

Response to Reviewers nhess-2017-98

Three-dimensional hydrodynamic lake simulations of avalanche-generated impulse wave dynamics for potential GLOF scenarios at Lake Palcacocha, Peru
Rachel E. Chisolm and Daene C. McKinney

Reviewer 1

General comments:

Lake Palcacocha – an emblematic case in GLOF studies – has been attracting attention of scientists as well as local authorities and practitioners since catastrophical outburst in 1941 (e.g., Oppenheim, 1946), resulting in implementation of remedial works (open cut and two artificial dams) in 1970s (Zapata, 2002; Emmer et al., accepted). Since that time, the lake has increased its volume from ca 0.5 Mm3 to about 17 Mm3 nowadays (UGRH, 2016), due to the glacier retreat, making these mitigation measures insufficient. Recently, Emmer et al. (2016) did lake inventory of lakes of the Cordillera Blanca (882 lakes identified, classified and described by the set of qualitative and quantitative characteristics) and assessment of susceptibility to outburst floods of all large lakes (A>100,000 m2; n=64), revealing that Lake Palcacocha is among those lakes ranked as "highly susceptible "to produce GLOF, moreover located upstream regional capital Huaráz. This study on the level of mountain range identified fast slope movements into the lake as likely trigger of GLOF from Lake Palcacocha, but does not provide more detailed information on them – apparent research gap which needs to be addressed. From this point of view is research on potential slope movements entering the Lake Palcacochca undoubtedly desirable.

The authors of the presented manuscript apply known methods and software in geographically relatively new context of Lake Palcacocha, focusing on uncertainties in modelling displacement wave dynamics (formation, propagation and dam overtopping). Comparison of results obtained from different methods / models is presented, however, with no validation against real GLOF event. This I found to be the major drawback of presented study – no real baseline is used, therefore models are compared to each other, but the overall value of obtained results and implications is, thus, somewhat uncertain.

Additionally, I'm convinced, that uncertainty of scenarios, methods and software used in entire process chain should be somehow balanced. Presented manuscript is, however, very much concerned about the uncertainties of methods and software used to simulate displacement wave dynamics, without considering factuality (uncertainty) of avalanche scenarios used. Why 0.5, 1.0 and 3.0 Mm3 ?? Why not e.g., 0.2, 2.0 and 5.0 Mm3 ?? Are there any field / remote sensing-based observations suggesting these volumes ?? This is major issue which needs to be addressed, otherwise all hazard mitigation implications and conclusions are rather speculative.

Moreover, Somos-Valenzuela et al. (2016) recently published modelling of entire process chain of outburst flood from Lake Palcacocha in HESS, considering the same ice avalanche and lake level lowering scenarios and using the same methods and software (Heller and Hager, 2010; FLOW3D, Flow Science, 2012). Releasing of this publication and submission of presented manuscript seems to me chronologically in reverse order, in other words, presented manuscript seems bit redundant now, when paper of Somos-Valenzuela et al. (2016) is published, despite the fact that presented manuscript provides "improved understanding of the dynamics of avalanche-generated waves". In conclusions, would presented results change the results of Somos-Valenzuela et al. (2016) in a significant way ?? Some of results presented are actually overlapping with Somos-Valenzuela et al. (2016), without mentioning it (the results presented in the first paragraph in section 3.4 are identical to results in the last paragraph in section 4.2.1 of Somos-Valenzuela et al. (2016)).

Novelty and additional value of presented manuscript compared to previous studies, therefore, need to be clearly shown, not only in terms of modelling (comparison of different approaches) but also in context of ongoing mitigation activities and research at Lake Palcacocha and realistic (observation-based) potential GLOF triggers.

Response to general comments from Reviewer 1:
We would like to thank the reviewer for taking the time and effort to review this manuscript and provide thoughtful and constructive comments. We hope that this work is a contribution to the overall understanding of GLOF processes as they relate to hazard assessment. We agree with this reviewer that field data for model validation would be a valuable addition to this work, however, this was not possible due to the lack of field data that could be used for model validation (This is discussed further below in response to specific comments regarding this point). Therefore, it was necessary to find alternative ways to evaluate the uncertainties in the lake model. This paper attempts to study one of the numerous sources of uncertainty in GLOF process chain modeling by applying three-dimensional modeling methods to avalanche-generated waves. The idea behind this approach is to attempt to compensate for our lack of knowledge about the precise characteristics of avalanche-generated wave during actual GLOF events by investigating the model sensitivities and potential sources of uncertainty while relying less on calibration and more on physical representation of the wave dynamics by using a 3D non-hydrostatic model. By attempting to understand the potential range of uncertainty in the lake model, we aim to present the results of a lake model with a realistic representation of the limitations of these results and how they might be used in the context of hazard mitigation.

The authors agree with the reviewer and recognize that the avalanche is potentially the greatest source of uncertainty in the entire GLOF process chain, but the consideration of uncertainties due to the avalanche entering the lake is beyond the scope of this work. As there are no field-based measurements or remotely sensed data that could justify changing the avalanche sizes used in this work (0.5, 1 and 3 x 10^6 m^3), we have decided to use values that are consistent with previously published studies for the Cordillera Blanca region. This work is an attempt to show a range of potential outcomes for an avalanche-triggered GLOF but does not address the uncertainties in the avalanche portion of the GLOF process chain. We do not currently possess the scientific knowledge to be able to precisely forecast or model avalanches, and investigating how avalanche dynamics are represented in models goes beyond the scope of this work. This paper addresses the uncertainties in the lake model itself and helps us gain a greater understanding of the parameters that are most likely to contribute to uncertainty in the lake model portion of a GLOF chain of events. We recognize that this is only one of many sources of uncertainty throughout the GLOF process chain, and evaluation of the relative contributions to the overall uncertainty from the individual processes is beyond the scope of this work. One of the major conclusions of this work is that the specific characteristics of the avalanche and how they are represented in the model have the greatest impact on the overtopping discharges. At present, the methods for reducing the uncertainty in the avalanche model do not exist, and given the relative lack of field data on avalanche characteristics in the region, even quantification of uncertainty in the avalanche characteristics would be nearly impossible. Therefore, three sizes were selected for the avalanche simulations (presented in Somos-Valenzuela et al., 2016) that are consistent with the literature on avalanche-triggered GLOFs in the region. Perhaps equally notable, however, are the parameters that are not significant contributors of uncertainty in the lake model. For example, the lake model is not very sensitive to the turbulence model, therefore a modeler attempting similar work in the future can select a turbulence model with greater confidence that it will not significantly impact the results.

We agree with the reviewer that it would have been better to have release this paper before Somos-Valenzuela et al. (2016), as this work was a precursor and necessary input to the hazard mapping results presented in Somos-Valenzuela et al. (2016). However, due to time limitations, priority was placed on disseminating the results for the entire process chain model and hazard mapping (Somos-Valenzuela et al., 2016) because we believed that the results and conclusions could have implications for decision making and hazard mitigation strategies. The results for the avalanche source boundary condition were used as inputs for the downstream inundation model and hazard map in Somos-Valenzuela et al. (2016), but this paper also presents a second boundary condition method, the mass-momentum source. The reason for showing in this paper the lake model results that are also presented in Somos-Valenzuela et al. (2016) is to allow for comparison between the two boundary condition methods as well as to explain some of the nuances of how the modeling methods influence the lake dynamics that could not be explained in Somos-Valenzuela et al. (2016) due to space limitations. We believe that the method of representing the avalanche impact with the lake (boundary condition method) significantly affects the overtopping characteristics, and because we cannot say that one is more correct than another, we present both in order to give an idea of the range of uncertainty. As is discussed in this paper, we believe that the mass-momentum source boundary condition method may be underestimating the overtopping volumes while the avalanche source boundary condition method may be overestimating overtopping. Therefore, the actual overtopping discharges that could occur in a real GLOF event might be somewhat less than what is presented in Somos-Valenzuela et al. (2016), but we do not have enough information or confidence in the model results to be able to say this with certainty. While this does not substantially change the conclusions made in Somos-Valenzuela et al. (2016) (even small avalanches could present a significant hazard to the city of Huaraz), it does shed light on the level of uncertainty. The differences between the two boundary condition methods are more pronounced for smaller avalanches, and this range of uncertainty indicates that overtopping may or may not happen for the lake-lowering scenarios with small and medium avalanches. While Somos-Valenzuela et al. (2016) concluded that lake-lowering could reduce the overtopping volumes and inundation extents, the results in this paper present a more optimistic outlook for the impact of lake-lowering in that it may be possible to prevent overtopping for smaller avalanches. The suggestion for clarifying this in the conclusion is a good one and has been noted; we have modified the results and conclusions sections to include a reference to Somos-Valenzuela et al. (2016) and clarify how these results influence the conclusions that can be made.

This work is not intended to repeat what is presented in Somos-Valenzuela et al. (2016) but to present additional results and details about the lake model. This paper presents findings about the sensitivities and uncertainties of a three-dimensional lake model due to several types of inputs, including the type of boundary condition representing the avalanche impact with the lake and model parameters such as the turbulence model and grid size. We have attempted to present this work in a way that emphasizes the sensitivity analyses, uncertainty and aspects of the lake model that were not presented in Somos-Valenzuela et al. (2016). However, we understand that the novelty of this work and the distinction from Somos-Valenzuela et al. (2016) may not have come across clearly in the way this manuscript was written. We have made some changes to the manuscript to attempt to clarify this distinction. The authors believe that it is important to share the complete results and conclusions of the lake modeling efforts because the findings could have significant implications for GLOF process chain modeling and the proper selection of modeling methods for avalanche-generated waves.

Specific comments and technical notes (key ones in **bold**):
Responses to specific comments are given in blue

P01L13: consider using the term “displacement wave“ in the manuscript
We agree with this suggestion, and it has been changed in the manuscript.

P02L11-16: see also recent lake inventory and GLOF susceptibility assessment for the Cordillera Blanca of Emmer et al. (2016)
We are familiar with this paper, and a reference has been added to the manuscript.

P02L23: “... failure of lake-damming moraine.“
This change has been made, and the manuscript now reads, “the primary characteristics that signify a potentially hazardous glacial lake are the presence of overhanging ice and the likelihood of failure of the lake-damming moraine.”

P02L24: see the work of Shiva Pudasaini and r.avaflow project (http://www.avaflow.org)
The authors have explored this model, and it appears that the model development has not yet reached a state to allow for 3D modeling of an avalanche-generated wave. When we discussed this with the model developers a couple of years ago, it was not yet ready for us to try, but it appears that the model is now available for download. The r.avaflow model looks promising in its capability to simulate multi-phase flows, and this could represent a significant advancement for the field of GLOF process chain modeling. However, this model seems to be focused on the interactions of the fluid and solid during impact and wave generation. The subsequent processes (wave propagation, run-up and overtopping) for avalanche-generated waves may be equally important to properly represent realistic overtopping volumes. Comparisons between 2D shallow water and 3D non-hydrostatic simulations indicate that the shallow water approximation is insufficient for representing the propagation and overtopping of this type of displacement wave (Heinrich, 1992; Zweifel et al., 2007; Somos-Valenzuela et al., 2016). The r.avaflow model uses depth-averaged equations for both the solid and fluid components of the flow. The use of a 2D

depth-averaged model for the propagation, run-up and overtopping phases may result in unrealistically optimistic overtopping volumes that could underrepresent the actual hazard levels. Nonetheless, we do believe that the r.avaflow model could be a great tool in GLOF process chain modeling, particularly for better understanding wave generation, and it is worth considering the use of this model in combination with 3D non-hydrostatic modeling of wave propagation in future studies of GLOF process chain modeling. We have been in communication with Shiva Pudasaini about this model, but unfortunately, the r.avaflow model was not ready for us to use when we did this work.

This model is an important contribution to the literature in the context of this work, and it was an oversight not to include references to it in the manuscript. We have added references to Pudasaini (2012) and Mergili et al. (2017) to the manuscript.

P03L04: "... may overtop or breach moraine dams."
We agree with this recommended change and have edited this to say: "These mass movement events can cause large waves that propagate across glacial lakes and may overtop or breach moraine dams"

P03L28: replace "potential" by "future"
We agree with this recommendation and have made this change in the manuscript.

P03L35-36: this needs to be specified in more detail; this has already been done as a part of Somos-Valenzuela et al. (2016)
We have added some text to this part of the manuscript to clarify the distinction between the two papers. The now states:

> "In this paper, Lake Palcacocha is used as a case study to investigate the impact of an avalanche event on the lake dynamics and the ensuing discharge hydrograph from the lake. This paper focuses exclusively on the lake dynamics for avalanche-generated waves and does not consider other parts of the GLOF process chain. The model results for the entire GLOF chain of events are presented in Somos-Valenzuela et al. (2016)."

P04L07: replace "mostly destroyed" by "breached"
We agree with this recommendation and have made this change in the manuscript.

P04L09: replace "a smaller" by "basal"
We have added "basal" to the description of the moraine that now retains the lake. This sentence now reads, "The original lake-damming terminal moraine was breached destroyed during the 1941 GLOF, and the lake is currently dammed by a smaller basal moraine that lies about 300 m upstream of the 1941 breach."

P04L09: replace "back" by "upstream"; for people who don't know this area, **field-based figure for better imagination** on that would be nice
We have changed "back" to "upstream", and we agree that this makes the description clearer.

P04L12: lake growth (glacier retreat) 200 m retreat since 2009 ?? please check

Rivas et al. (2105) documented the growth of Lake Palcacocha with Aster imagery, and the retreat of the lake between 2009 and 2012 can be seen in Figure 4 of Rivas et al. (2105). This reference has been added to the manuscript.

P04L17: replace “terminal“ by “damming“
This has been changed to read, “The southern lateral moraine is prone to landslides into the lake, and a slide from this moraine in 2003 caused minor damage from a wave that overtopped a portion of the lake-damming moraine (Vilimek et al., 2005).”

P04L19-32: here, I miss two recent works focusing on Lake Palcacocha: Emmer et al. (2016) identifying Lake Palcacocha as highly susceptible and Klimeš et al. (2016) elaborating impact of potential landslides in moraines on the Lake Palcacocha (sorry, I contributed to both)
We agree that these are relevant sources, and these references have been added to the manuscript.

P04L01-P05L15: see also Westoby et al. (2014, 2015), Pudasaini & Hutter (2007); Mergili et al. (2016), r.avaflow project (r.avaflow.org) and others
References to r.avaflow (Pudasaini, 2012) and Mergili et al. (2017) have been added to the manuscript. Westoby et al., 2014 has already been included in the reference list, and the Westoby et al. (2015) and Pudasaini and Hutter (2007) references were not included because they focus on portions of the GLOF process chain (avalanche dynamics and moraine breaching) that are not considered in this paper. This comment also appears below for P7L17-24.

P05L32-33: if it is true that the glacier retreated 200 m since 2009 (see P04L12), 2016 lake bathymetry should be used in order to obtain meaningful results
The 2016 bathymetric survey was not undertaken until after the modeling work was completed, therefore it was not possible to include the bathymetric data from 2016 in the lake model.

P06L05: how do you know these are “likely avalanche sizes“ ?? Why 0.5, 1.0 and 3.0 Mm3 ?? Why not e.g., 0.2, 2.0 and 5.0 Mm3 ?? Are there any field / remote sensing-based observations suggesting that ?? please explain and elaborate in detail
The avalanche scenarios used in this work are the same as the avalanche simulations published in Somos-Valenzuela et al. (2016). These avalanche sizes were selected based on other similar studies in the Cordillera Blanca region (e.g., Schneider et al., 2014) as well as considering a range of avalanche sizes that might be expected given the conditions of the glacier. While we recognize that other avalanche sizes are possible, these scenarios were selected to represent a range of potential outcomes and were not meant to be a comprehensive analysis of all possible avalanche sizes that could originate from the Palcaraju and Pucaranra glaciers. The justification for the three avalanche sizes used in this work is presented in more detail in Somos-Valenzuela et al. (2016).

P06L07: why this baseline ?? this explanation (“appropriate mixing length was unknown“) is not clear to me
It was necessary to select a baseline model to which other turbulence model results could be compared in order to facilitate the analysis of the turbulence model sensitivity (the point of comparison for all models must be consistent). The mixing length is a parameter in many

turbulence models that must be specified by the user; it is a length scale used for the calculation of values within a turbulence model. Typically, a length scale for a turbulence model would be based on the flow conditions (e.g., depth of flow in a river), but because the conditions for avalanche-generated waves are so highly variable (both spatially and temporally), there is no length scale that would be an obvious choice for these simulations. Examples of some possible length scales include lake depth or wave height, but the correct length scale for a turbulence model depends highly on the flow conditions, and neither of these is likely an appropriate choice. The "dynamically-computed mixing length" is an option in some turbulence models that allows the model to determine the mixing length based on localized flow conditions (the mixing length varies throughout the simulation). For this reason, the RNG model with a dynamically-computed mixing length was selected as the point of comparison for other turbulence models because it eliminates the uncertainty of the mixing length parameter as a possible influence on the model results. It turns out that the model is not very sensitive to this parameter, but for consistency in comparisons between models, it was necessary to eliminate this variable in the baseline turbulence model.

P07L17-L24: see also Westoby et al. (2014, 2015), Pudasaini & Hutter (2007); Mergili et al. (2016), r.avaflow project (r.avaflow.org) and others
See response to the same comment on P4L1-P5L15

P07L35-P08L02: this implication is not clear to me, please explain in more detail
The momentum transfer from the avalanche to the lake is what generates the displacement wave. Thus, the wave characteristics depend both on the mass (equivalent to depth) and velocity of the avalanche as it enters the lake. If the avalanche source model can reasonably reproduce those characteristics of the avalanche in the flow entering the lake, then the representation of the wave generation in the model should reasonably approximate the wave generation characteristics that could occur during an actual GLOF event.

P08L25: replace "terminal moraine" by "dam"
The manuscript on P9L4 has been changed to read, "The primary parameters used to study the wave characteristics were the maximum height of the wave in the lake and the wave height as it overtopped the moraine dam."

P08L29: why not to use 2003 GLOF for the validation ?? yes, it was not ice avalanche-triggered GLOF (landslide in lateral moraine), but formation, propagation of displacement wave and dam overtopping occurred; please comment on that
In an ideal world, we would use data from past GLOF events such as the 2003 landslide into Lake Palcacocha from the lateral moraine to validate the model. However, we do not have enough data on the event itself to be able to do this. In order to use field data for model validation, we would need information on parameters such as wave heights, landslide characteristics, etc. It is true that we have some information on the 2003 landslide, but the only variable that is known with reasonable confidence is the landslide volume; we would also need information on the depth and/or velocity of the landslide to be able to estimate the momentum that would have been transferred to the lake to generate the overtopping wave. All we know for certain from that event is that the terminal moraine was overtopped (minimum run-up height of ~8 m) and the moraine structure was partially damaged, but we cannot back-calculate the

characteristics of the overtopping wave to the level that would be needed for model validation. Additionally, the landslide entered the lake from the lateral moraine, so the direction of propagation would have been different from the avalanches considered here that would enter the lake along its primary axis (in the same direction as the long axis of the lake and perpendicular to the moraine dam). Thus, the wave from the 2003 landslide may have been reflected off the lateral moraines before reaching the damming moraine; this would be a source of energy dissipation that could reduce the overtopping discharge. A wave that enters the lake along the primary axis and is not reflected off of a lateral moraine could result in higher overtopping discharges.

P09L18-L20: is that what is actually being done currently ?? if hazard mitigation implications are elaborated, more info on ongoing works should be provided
Lake lowering is being considered by government officials, and based on personal conversations with those involved in the planning and decision-making, 30 m is the lowest lake lowering alternative that is being seriously considered, as further lake lowering (beyond 30 m) would likely not be feasible. More information on the downstream impacts of these scenarios is given in Somos-Valenzuela et al. (2016). However, as of yet, no decisions have been about concrete mitigation measures. One of the objectives of this work and the work presented in Somos-Valenzuela et al. (2016) is to provide information that can assist decision-makers in Huaraz with making more informed decisions about hazard mitigation alternatives. We are not, however, making definitive recommendations about what actions should be taken.

P13L08-L16: similar to last paragraph in section 4.2.1 of Somos-Valenzuela et al. (2016)
Because it was necessary to present some of the same results from Somos-Valenzuela et al. (2016) for the sake of comparison between the various input parameters and boundary conditions, the explanation of the results that we show is indeed similar. The parameters presented with the results in this section (Section 3.4) are key parameters for understanding the characteristics of the overtopping discharges, and in order for the reader to understand the results we present here, it was necessary to give some explanation of the parameters considered. They may be similar, and this is unavoidable, however, this paragraph does not directly repeat what was stated in section 4.2.1 of Somos-Valenzuela et al. (2016).

P14L01: replace "damming moraine" by "dam"
We believe that changing the term "damming moraine" to "dam" implies that the structure retaining the lake is entirely man-made, so we have decided to leave this as it is to ensure that readers understand that what holds the lake back is primarily natural moraine.

P14L18-P17L11: this is hard to follow; I strongly recommend to **structure discussion into the sub-sections reflecting individual issues discussed**
This is a good recommendation, and this section has been re-structured to include sub-headings for the different topics that are discussed.

P14L31-L33: see also avaflow.org
This is a relevant point, and a sentence has been added to the manuscript to discuss how multi-phase debris flow models such as r.avaflow relate to the work presented in this paper:

> "Recent advances in two-phase flow models such as r.avaflow (Pudasaini, 2012; Mergili, 2017) can facilitate simulations of wave generation from avalanches entering a lake; however, the use of depth-averaged

equations still limits the ability to use this type of model to simulate all of the phases of an avalanche-generated wave from wave generation to overtopping."

P15L02-L07: comparing different models between each others with no comparison to reality seems slightly purposeless to me

Unfortunately, there are insufficient field data for this type of avalanche-generated wave to allow for comparison of model results with actual GLOF events. Wave characteristics such as wave height and attenuation would be needed to do this comparison, but they do not exist. The types of data that we have from previous events such as the 2003 landslide at Lake Palcacocha generally consist of estimates of the total slide volume and the run-up heights of the waves on the terminal and/or lateral moraines. We can see in the 3D simulations of avalanche-generated waves that are presented in this paper that the wave heights and run-up heights are very different. The theoretical run-up height against a vertical wall is twice the wave height, but in natural environments, the actual run-up height is highly dependent on the field characteristics (eg., lakebed geometry and moraine slope). Additionally, for many GLOF events, even the run-up height is not known with certainty. In many cases, only the minimum run-up height is known because overtopping of the damming moraine was observed, so it was concluded that the run-up height must have been greater than the freeboard. In the case of the Lake 513 event, the wave height was estimated to be 25 m based on the 20 m freeboard of the rock dam and the 5 m of debris that were eroded by the overtopping wave; however, this is not an accurate estimate of the actual height of the avalanche-generated wave within the lake, and it is possible that the run-up height/overtopping wave height was greater than 25 m.

Because field data were not available, we had to look for alternatives to check the reasonableness of our results. The empirical model has been compared to measured data and laboratory experiments (a form of validation of the method), so it may reasonably be concluded that if the 3D model gives similar values for the wave characteristics, we can have more confidence in the 3D model. However, this comparison is only valid for the wave generation phase (maximum wave height), as the empirical model does not represent the wave propagation, run-up and overtopping phases well (if at all).

Because we have so little information about field characteristics of avalanche-generated waves, our best course of action to facilitate understanding of the wave dynamics is to use models that depend less on calibration (such as 2D SWE models) and more on better model representation of the physical processes (e.g., the 3D non-hydrostatic model that is used here). When model calibration and validation with field data is impossible, another necessary step is to investigate the model sensitivity to input parameters. This sensitivity analysis must be used in lieu of validation in order to better understand on the uncertainties of the model so that we do not represent more confidence in the model results than is justifiable given the uncertainties in the modeling process. Even though field data are not available to validate our model results, we believe that this should not prevent us from attempting to make progress in the methods for modeling avalanche-generated waves while still recognizing the limitations of our work.

P16L19: from my point of view, the greatest uncertainity arises from not knowing realistic (field investigation-based) scenarios of potential ice avalanches entering Lake Palcacocha, making all hazard mitigation implications and conclusions rather speculative; please discuss that

This is true; we recognize that the avalanche is the portion of the GLOF process chain is the least understood and most likely the greatest source of uncertainty in GLOF modeling and hazard mapping. Although the uncertainty resulting from the avalanche portion of the chain of events must be considered in the decision-making process, investigating the uncertainty in the avalanche characteristics is beyond the scope of this work. This paper focuses exclusively on the lake dynamics of avalanche-generated waves and what are the potential sources of uncertainty in this portion of the GLOF process chain. In a way, the avalanche scenarios are attempting to capture some of that uncertainty, but it does not represent all of the uncertainty associated with the avalanche model. This work explores the uncertainties that arise when representing the impact of the avalanche with the lake and the wave generation, but this is necessarily limited by the avalanche characteristics that were available from the avalanche simulations. Until further advances are made in the field of avalanche simulations and we gain an improved understanding of avalanche dynamics for this type of event, it is impossible to incorporate all of the uncertainty of potential avalanches into analysis of the dynamics of avalanche-generated waves. All that we can do is assess the sensitivity of the lake model to different types of inputs to gain a qualitative understanding of how these uncertainties might impact the characteristics of avalanche-generated waves and the overtopping discharges.

Nonetheless, it is clear that steps to mitigate or reduce the hazard must be taken because even with the low end of the range of uncertainty in avalanche sizes, the resulting discharges could represent an unacceptable level of risk for the city of Huaraz. This is treated further with the hazard and inundation intensity maps for the various scenarios in Somos-Valenzuela et al. (2016).

We have modified the discussion section to more clearly convey this idea.

P17L06-L08: please add reference
A reference to Huggel et al. (2004) has been added to the manuscript.

P17L13-L14: improving the understanding of lake dynamics during GLOFs does not necessary require the use of 3D non-hydrostatic models only, this is just an option; please reformulate
We agree that the way this is worded is misleading, and this sentence has been changed in the manuscript to read: "Three-dimensional non-hydrostatic models can be a useful tool to simulate avalanche-generated waves and improve our understanding of lake dynamics during GLOF events."

While 3D non-hydrostatic models may not be required to improve our understanding of avalanche-generated waves, they are a very useful tool, especially given the lack of field observations. It is clear that 2D SWE models are insufficient for representing the dynamics of displacement waves, especially during the propagation, run-up and overtopping phases (Heinrich, 1992; Zweifel et al., 2007; Somos-Valenzuela et al., 2016). The hydrostatic approximation has a significant effect on the dissipation of energy, so hydrostatic models are likely to be severely underestimating overtopping discharges. Therefore, unless a calibration procedure is used similar to the one presented in Somos-Valenzuela et al. (2016) to compensate for this dissipation of energy, a non-hydrostatic model is necessary to represent the dynamics of an avalanche-generated wave.

P17L16-L17: this is very apparent
Yes, it is obvious that larger avalanches pose the greatest threat, but the main point we were attempting to make is that even smaller avalanches could pose a threat that should not be ignored. The manuscript has been changed to read, "While large avalanches pose the greatest threat to the city of Huaraz, even smaller avalanches could generate significant overtopping discharges, resulting in substantial inundation in the city."

P17L22-L24: hazard level for Huaráz is not the subject of the manuscript, this conclusion is more based on work of Somos-Vlaenzuela et al. (2016); please rerformulate or avoid Simulation vs. modelling – is there any difference ?? please explain and unify in manuscript
That is correct; this paper does not address the downstream impacts of overtopping, as these are discussed in Somos-Valenzuela et al. (2016). The only conclusions that are made here refer to the overtopping of the lake-damming moraine. The point here is that overtopping could possibly be prevented (or reduced) for smaller avalanche scenarios through a lake-lowering mitigation project. It necessarily follows that if there is no overtopping, then potential hazards downstream could be prevented. It is not necessary to analyze downstream events to come to this conclusion. We may also conclude solely based on the results of the lake model that if overtopping discharges can be reduced by lake lowering, then the downstream hazard can also be reduced; exactly how much the downstream hazard can be reduced is not discussed in this paper and goes beyond the scope of this work (as it is presented in Somos-Valenzuela et al., 2016).

Tab 2: if the wave height is defined as "height above the moraine crest as the wave overtops the damming moraine" (P13L10) it is not clear to me, why is increasing with decreasing lake level (volume, peak discharge) ?? please elaborate in more detail
This is indeed a strange relationship, and upon first looking at it, it seems counterintuitive. However, we believe that this relationship of increasing wave heights above the moraine crest at the point of overtopping is physically correct. An explanation of this is given in the text (P14L11-17 of the manuscript) and has been modified to add additional clarity. The modified text is copied below.

"The overtopping wave heights increased with lake lowering even though the total overtopping volumes and peak flow rates decreased. This may seem counterintuitive, but it can be explained by looking at how the lake dynamics may be expected to change with lake lowering. First, as the water surface level is lowered, the total volume stored in the lake increases, thus the momentum transferred to the lake from the avalanches per unit volume should be higher. The total volume in the lake decreases with lake lowering, so the additional momentum relative to the lake volume can produce taller waves. Secondly, as the point of avalanche impact is at a lower elevation relative to the avalanche release area with lake-lowering, there is more momentum in the avalanche fluid when it enters the lake. Although the increased overtopping wave heights for the lake lowering scenarios indicate that the waves may be larger when the lake is lowered, the amount of overtopping still decreases with lake lowering. This is most likely due to the lower initial water surface elevation; the lower free surface elevation results in a larger freeboard and means that more momentum is required for overtopping; although the momentum transfer per unit volume to the lake from the avalanche is greater, more of this momentum is lost during the run-up and overtopping, and less water is actually able to pass over the crest of the terminal moraine."

Based on above mentioned I suggest major revisions of the manuscript. I'll be happy to review revised version. Please, do not hesitate to contact me in case of questions (aemmer@seznam.cz).

Kind regards
Adam Emmer

References (style not unified, sorry):

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Reviewer 2

General Comments

The manuscript has many overlaps with the HESS paper by Somos-Valenzuela et al. (2016). Yet, there is sufficient novelty and originality that warrant publication of this manuscript for which NHESS is a suitable outlet. This added value, however, should be addressed more rigorously before the manuscript is ready for publication. The main strength of the paper lies in the sensitivity analysis of numerical models of displacement wave generation, propagation, run-up and overtopping. A revised manuscript should accentuate this issue, both in the title and overall focus. So far, the paper emphasizes the GLOF hazard of Lake Palcacocha and conveys a case study rather than a more general treatment of the problem. I am sure that this would help to demarcate the paper against the paper by Somos-Valenzuela et al. (2016).

A stronger focus on sensitivity analysis would entail to shorten several of the general issues raised in the introduction but rather extend on the issues in section 1.2. A clearer distinction should also be made between the sensitivity assessment and the scenarios. So far, uncertainties that arise from the avalanche simulation process are mixed with the assumptions about the size of the avalanches or the scenarios, in general. Sensitivity analysis is closely related to the analysis of uncertainties and how they propagate to measures relevant for decision makers. The crisp values listed in Table 2 and 3, and classification of scenarios into "safe" and "not safe" appear at odds with a probabilistic assessment but should rather incorporate uncertainty characterization which could either be quantitative (Table 2,3) or qualitative (Table 4) and derived from the sensitivity analysis.

I think that my concerns about the current manuscript can be addressed but need substantial rewriting or restructuring. Moreover, additional analysis may be required. I thus recommend major revisions.

Response to General Comment from Reviewer 2:
The authors would like to thank Reviewer 2 for the thoughtful feedback on this manuscript. The Reviewer's comment on the focus of this manuscript is correct. This paper is not meant to be a re-hashing of the lake model results from Somos-Valenzuela et al. (2016) but rather a

complementary paper that focuses on the dynamics of avalanche-generated waves and the analysis of sensitivity to input parameters and boundary conditions. Very little work has been done in this area, especially with three-dimensional lake models, so we believe that the sensitivity analyses presented here can help future GLOF process chain modelers to better represent the dynamics of avalanche-generated waves and their overtopping characteristics. We recognize that the distinction between this paper and Somos-Valenzuela et al. (2016) may not have been clearly communicated in the manuscript, and are making changes to make this distinction more clear. We are considering the reviewer's suggestion to focus more on the sensitivity analysis in the revision of the manuscript, and we appreciate your specific suggestions on how to achieve this.

Regarding the definition of "safe" and "not safe" for the overtopping scenarios, we recognize that this terminology may not be accurately representing what we are trying to communicate. We are simply trying to clearly present which scenarios resulted in overtopping, but we do not intend this to replace probabilistic analysis of the scenarios and their relation to potential downstream hazards. The only thing we intend people to take away from this analysis is that if there is no overtopping, then that could prevent downstream inundation. Therefore, we are revising how this is presented in Table 4 to indicate the scenarios where overtopping did or did not occur. In addition, we are revising the accompanying explanatory text to more clearly communicate that these results to do not definitively indicate whether or not overtopping will occur but rather give a general idea of whether or not overtopping is likely. We do not attempt a probabilistic assessment of the hazard for each scenario nor a quantitative assessment of uncertainty, because it goes beyond the scope of this work, and we do not have sufficient information to do this. However, we would like to communicate more transparently what we are attempting to do and how this work relates to the larger problem of hazard assessment. Recognizing the limitations of our work is important to interpreting and applying the results, and we do not intend to imply more than what we have done in terms of hazard assessment and evaluation of mitigation alternatives. To fully analyze downstream impacts of mitigation alternatives and determine an optimum lake level requires consideration costs and benefits; further analysis beyond just the lake model is necessary, and this analysis is beyond the scope of this work. The overtopping discharges should not be considered in isolation when evaluating lake lowering and hazard mitigation alternatives. This paper does not attempt to address the decision-making process but only to provide information that might be useful inputs to that process.

In response to your comments, we are looking at ways to re-organize the paper and focus on the uncertainties and sensitivity analysis. While it is necessary to use some of the lake modeling results that are published in Somos-Valenzuela et al. (2016) for the sake of comparison with other methods and input parameters, we intend that this paper to be a separate work that shows what parameters in the lake model are most important to consider (where the model is most sensitive to inputs) and where the greatest sources of uncertainty in the lake model are likely to come from.

While there are many more parameters that we would like to be able to analyze, due to limitations in the time of the software license, we are not able to run any more simulations for further analysis.

Specific comments:
Responses to specific comments are given in blue.

1, 11: risk in the risk literature is defined as average loss per year. I'd replace the term risk with probability.
While there are many definitions of risk in the literature, you are correct that in the context of hazards, risk has a precise definition that includes hazard (combination of intensity and probability) and vulnerability. We believe that risk assessments should be the ultimate goal, but the work we do only deals with the hazard component. In this sentence, the intent is to convey a sense of the general threat to downstream communities from glacial lakes in the Cordillera Blanca, and we agree that while technically correct, the use of the word "risk" here may be misleading. Therefore, the word "risk" has been replaced with "threat" in the manuscript.

2, 2: perhaps rephrase: "..., and Schwanghart et al. (2016) showed that more than 68% of Himalayan hydropower projects are located on potential GLOF tracks".
This is a good suggestion that more clearly conveys the idea, and the manuscript has been changed accordingly.

2, 10: It is unclear what the 40% refer to. 40% more lakes than before 1986?
We agree that this wording is unclear and appreciate you pointing it out to us. The manuscript has been changed to read: "Cook et al. (2016) studied glaciers in the Bolivian Andes where glaciers have receded about 40% between 1986 and 2014, resulting in an increasing number of proglacial lakes."

2, 19: Can you briefly explain, why this is so? Is there something special about the moraines in the Cordillera Blanca? Or is the statement more general, i.e., that morainedammed lakes are more susceptible than bedrock or ice-dammed lakes?
In general, moraine-dammed lakes are more susceptible because failure of the moraine dam is an additional factor that could cause a GLOF (a potential GLOF trigger that is not present with rock-dammed lakes). Moraine dams are not exclusive to the Cordillera Blanca, but this region has a high number of lakes that are moraine-dammed, so the potential for moraine failure is a factor that should be considered as part of GLOF hazard assessment if a lake is moraine-dammed. Emmer and Cochachin (2013) further discuss the mechanisms of moraine-dam failures and how this varies from region to region. To clarify this point, the manuscript has been changed to:

"Moraine-dammed lakes such as those present in the Cordillera Blanca are particularly susceptible to outburst flooding due to the potential for moraine failure that could cause higher GLOF discharges than would occur with just overtopping (Emmer and Cochachin, 2013); however, both moraine-dammed and bedrock-dammed lakes can produce potentially catastrophic GLOFs due to overtopping if there is insufficient freeboard."

2, 29: any reference to back the statement that lake dynamics remain one of the most problematic processes?
In general, lake dynamics for avalanche-generated waves have not been studied in detail, and we have very little in-situ data (almost none) from GLOF events. Several sources say that 2D SWE

models don’t represent the dynamics of this type of wave well (Heinrich, 1992; Zweifel et al., 2007; Worni et al., 2014; Somos-Valenzuela et al., 2016), but 3D models have not been used in this context before. Most process chain modeling studies use 2D SWE lake models (e.g., Schnieder et al., 2014; Worni et al., 2013). Because the hydrostatic approximation has a significant effect on the dissipation of energy, GLOF process chain simulations that use 2D SWE models are likely to be severely underestimating overtopping discharges. This paper attempts to address this research gap by investigating the use of a 3D non-hydrostatic lake model.

To clarify this point, the text in the manuscript has been changed to read, “however, the lake dynamics remain one of the most difficult processes to simulate correctly due to the need for a non-hydrostatic model to correctly represent the wave dynamics (Heinrich, 1992; Zweifel et al., 2007; Worni et al., 2014) and the lack of field data for model calibration or validation.”

3, 6: The abbreviation SWE (shallow water equations?) has not been introduced before.
Thank you for pointing this out. It has been corrected in the manuscript.

3, 18: specify "this area"
This is indeed a vague reference, and the manuscript has been changed to read, “Huaraz is the most populous city in the Cordillera Blanca region”

4, 5: Please provide more quantitative information on the moraines here.
Information on the moraine slopes has been added to the manuscript as well as information on the width, height and width-to-height ratio of the lake-damming moraine. The edited text now reads, “The lake is surrounded on three sides by glacial moraines, and the lateral moraines are very tall with slopes up to 80º (Klimes et al., 2016). The southern lateral moraine is prone to landslides into the lake, and a slide from this moraine in 2003 caused minor damage from a wave that overtopped a portion of the lake-damming moraine (Vilimek et al., 2005). The original lake-damming terminal moraine was breached destroyed during the 1941 GLOF, and the lake is currently dammed by a smaller basal moraine that lies about 300 m upstream of the 1941 breach. This smaller moraine that currently holds back the lake is approximately 66 m deep, 985 m wide and has a width-to-height ratio of 14.9; this morphology indicates that the lake-damming moraine is very stable (Rivas et al., 2015).”

4, 33: I’d avoid the term "complex" here, in particular since you continue with "To complicate matters further...". Complex is not complicated.
It is a true statement that slide-generated waves have complex dynamics, and references from the literature have been added to the manuscript to support this statement (Worni et al., 2014; Fritz et al., 2004). The edited text in the manuscript now reads, “The dynamics of avalanche or landslide-generated waves are very complex (Fritz et al., 2004; Worni et al., 2014). In addition, it is very difficult to obtain field measurements of these waves to better understand their dynamics.”

6, 10f: I am not an expert in computational fluid dynamics, and have problems understanding this part. To avoid that readers get lost here, please try to use plain language to explain the issues with the turbulence model. Otherwise, this part is extremely technical when compared to the preceding part of the paper.

We appreciate this feedback, especially from those who are less familiar with CFD because we would like for this to clear to all readers. We especially believe that it is important to communicate this clearly to non-CFD specialists because many involved in GLOF process chain modeling come from backgrounds other than engineering and computational fluid dynamics, and we hope that this paper can assist them in selecting appropriate modeling methods and efficiently concentrating their efforts to get more accurate estimates of overtopping discharges. While we don't want to lose any of the technical rigor of the turbulence model sensitivity analysis in how this is communicated, we want this to be understandable to both the CFD experts and scientists in other fields. The main point we want to convey is that we evaluated a number of turbulence models and determined that the uncertainty resulting from the turbulence model is small when compared to the uncertainty resulting from other aspects of the model. This portion of the manuscript is being revised to address this concern.

6, 18: Here scenarios are mentioned, but are later explained in 2.4. Consider rearranging the headings.
We believe that changing the order of the sub-sections here would not present things in a logical order (the scenarios really are the last thing considered and we use the work presented in prior sub-sections as a basis for the scenario analysis). To resolve the problem of referring to scenarios before they are mentioned, we have removed the reference to the scenario here and simply referred to the characteristics of the inputs used for the turbulence model sensitivity simulations.

7, 1f: What is the source of the elevation and bathymetry data?
The lake bathymetry used in this model comes from a 2009 bathymetric survey done by the Peruvian Glaciology and Water Resources Unit (called UGRH from the name of the unit in Spanish). This is stated at the beginning of Section 2 (P5L32-33). However, we neglected to state the source of the topographic data. The topography of the surrounding terrain comes from Horizons (2013). This reference has been added to the manuscript. We apologize for this oversight.

7, 10: I think this should be interpolation, not extrapolation.
This is not interpolation. We are simply assigning the same values to the 4 smaller cells that fall within each cell in the coarser grid. To clarify this, we have modified the text to read, "For the coarse grid simulations, the same value for water depth at each time step in the coarse grid was assigned to the four smaller cells that fall within each cell in the coarser grid to allow for direct comparison between the results of the coarse grid simulation and the regular mesh."

7, 16: not easy to solve: avoid subjective statements
This text has been modified to read, "The problem of reproducing an avalanche-generated impulse wave in a hydrodynamic model of a glacial lake presents a challenge because of the complicated dynamics of mixing and dissipation of energy that occur at the point of impact; these processes are difficult to represent correctly in the model."

8, 20: provide reference to empirical methods
A reference to the empirical method that is used in this work (Heller and Hager, 2010) has been added here.

8, 27f: This point has been mentioned before. I'd delete this part.
This portion of the text has been edited to remove redundancies.

10, 8: Avoid interpretation here
You are correct that interpretation is inappropriate here in the results section. This sentence has been changed in the manuscript to read, "The laminar model shows high deviations from the baseline model because it does not account for turbulence and should be the least dissipative of all the models."

10, 6: It is a bit unsatisfactory that there is a baseline level of error due to the extrapolation of the initional conditions to a coarser grid. Any chances to overcome these issues? Otherwise, it is difficult to separate the sensitivity to initial conditions and sensitivity to grid size.
This is simply because the bathymetry and thus initial still water depths cannot be represented as well with the coarser grid (the resolution of the bathymetry must be the same as the resolution of the model grid, so we lose some of the precision of the bathymetric representation that the finer grid has). We do not think there is any way to overcome this, but we have added a sentence to the manuscript to clarify this point. The modified text now reads: "However, there was a baseline level of error that comes simply from extrapolating the initial conditions to a coarser grid because the bathymetry and initial fluid depths are better represented in the fine grid model; this baseline error was unavoidable because the resolution of the bathymetry must be the same as the resolution of the model grid, so we lose some of the precision of the bathymetric representation in the model with the coarse grid."

12, 27: I would avoid the term tsunami in this context. Rather call it a displacement wave.
This change has been made in the manuscript, and it now reads, "The impact of the avalanche with the lake generates a large displacement wave."

14, 19f: The first paragraph should rather be placed in the introduction or removed.
This is a good suggestion, and this change has been incorporated into the re-organization of the manuscript.

16, 14: remove somewhat
This change has been made in the manuscript.

Figure 1: Consider using hillshading to better visualize topography (see Fig. 1 in Somos-Valenzuela et al. 2016). In addition, adding glaciated areas would be helpful.
We have considered this suggestion, and we decided that the current figure is adequate for the purposes of this paper.

Reviewer 3

General Comment:

General remark I appreciate that several research teams work in this area and different techniques could lead to better understanding of process related to natural hazards. I believe that such paper about modelling will be very useful, nevertheless if there were already published quantifications which might be used to verify the presented model, they should be used. I will understand if such verification will be already to large extension of submitted paper, but in this case it should be considered in the Discussion. I mean the: height of the wave overtopping the dam in 2003 (8 meters) or estimation of landslide volumes on the inner parts of lateral moraine (see papers Vilímek et al., 2005 and Klimeš et al. 2016).

Response to General Comment from Reviewer 3:
We would like to thank Reviewer 3 for the helpful comments on this manuscript. We agree with the point you make that validation of this model with field observations would be very useful. Unfortunately, the data we do have from previous GLOF events are insufficient for validation of this type of model. The 2003 landslide into Lake Palcacocha that you mention does have some information. In particular, we have a reasonable approximation of the landslide volume and the minimum run-up height over the lake-damming moraine complex. The estimate of the wave height in Klimes (2005) is based on the fact that the lake-damming moraine that had a freeboard of 8 m was overtopped. However, this would, in fact, be the minimum run-up or overtopping height and is different from the height of the wave within the lake. The actual height of the overtopping wave above the moraine crest is unknown. We have also found that the lake model is very sensitive to the characteristics of the mass movement into the lake (landslide or avalanche depth and velocity), and these parameters are not known precisely for the 2003 landslide at Lake Palcacocha. In order to do a meaningful comparison of this event with the results from the simulations of the lake model, we would need more information on the characteristics of the landslide other than just volume. This is something we would like to have been able to do, but unfortunately it was not possible with the available data.

However, your point about model validation is a good one, and we expect that many readers would have the same question that you present. We have added text to the discussion to address this issue more clearly.

Specific comments:
Responses to specific comments are given in blue.

P1 L29: I suggest: ": : :: : :a large number of these lakes pose a hazard or risk: : :" This is general sentence about GLOFs worldwide, not only about Palcacocha lake.
This change has been made to the manuscript, and the sentence now reads, "Glacier retreat worldwide has resulted in the emergence and growth of glacial lakes that have replaced ice in the tongue area of many glaciers, and a large number of these lakes pose a hazard or risk of glacial lake outburst floods (GLOFs)."

P2 L18: not only moraine-dammed lakes could be mentioned here, but also bedrock-dammed lakes (due to possible dam overtopping).

In general, moraine-dammed lakes are more susceptible because failure of the moraine dam is an additional factor that could cause a GLOF (a potential GLOF trigger that is not present with rock-dammed lakes), and this is all this sentence was meant to convey. However, you are correct that there is still a significant potential for GLOFs due to overtopping with bedrock-dammed lakes. The manuscript has been changed to clarify this and now reads,

“Moraine-dammed lakes such as those present in the Cordillera Blanca are particularly susceptible to outburst flooding due to the potential for moraine failure that could cause higher GLOF discharges than would occur with just overtopping (Emmer and Cochachin, 2013); however, both moraine-dammed and bedrock-dammed lakes can produce potentially catastrophic GLOFs due to overtopping if there is insufficient freeboard.”

P2 L19-23: do not forget about rock-slides or rock-avalanches here,
You are correct that the potential for rock-slides or rock-avalanches are other factors that influence the potential for a lake to produce a GLOF. These factors have been added to the manuscript that now reads, “According to studies that have established basic methods for evaluating potential glacial lake hazards (e.g., Haeberli et al., 1989; Huggel et al., 2004; Wang et al., 2011; Emmer and Vilímek, 2014; Rounce et al., 2016), the primary characteristics that signify a potentially hazardous glacial lake are the presence of overhanging ice and the likelihood of failure of the lake-damming moraine; secondary characteristics that in indicate potentially dangerous lakes include the potential for landslides, rock-slides or rock-ice avalanches.”

P3 P3-4: this sentence should consider not only overtopping of moraines, but also breaching of moraines and overtopping of bedrock dams.
The manuscript has been changed to reflect this suggestion, and this sentence now states, “These mass movement events can cause large waves that propagate across glacial lakes and may overtop or breach moraine dams or cause overtopping of bedrock dams.”

P4 L5: the steepness should be specified (inner and outer slopes). And be careful, because the current moraine holding the water behind (in lake frontal part), which you named “smaller moraine” on P4 L8 is rather different (in the steepness and not only) from the older one which was in function before 1941. This is clear for those who know the area personally, but not for all. I strongly suggest you to add a photo, on which you can explain the situation (like FIG. 1, perhaps better taken from the right lateral moraine). There exist another publication directly from the area of interest (Novotny and Klimeš, 2014), where you will find parts dedicated to steepness of slopes; for instance: “Investigations of mechanical and strength properties showed that the inner moraine slopes maintain temporal slope stability despite their steep dip (very often above 50), which exceeds the dip of tested strength parameters. Their values are around 40 “.
Information on the moraine slopes has been added here. The type of moraine that currently dams the lake has been clarified in the manuscript (now referred to as a smaller basal moraine to distinguish it from the larger terminal moraine that was breached in 1941). The description of the moraines in the revised text is copied below:

“The lake is surrounded on three sides by glacial moraines, and the lateral moraines are very tall with slopes up to 80º (Klimes et al., 2016). The southern lateral moraine is prone to landslides into the lake, and a slide from this moraine in 2003 caused minor damage from a wave that overtopped a portion of the lake-damming moraine (Vilimek et al., 2005). The original lake-damming terminal moraine was breached destroyed during the 1941 GLOF, and the lake is currently dammed by a smaller basal moraine that lies about 300 m upstream of the 1941 breach. This smaller moraine that currently holds back the lake is approximately 66 m deep, 985 m wide and has a width-to-height ratio of 14.9; this morphology indicates that the lake-damming moraine is very stable (Rivas et al., 2015)."

P8 L23: I like the fact that you consider the lake bathymetry and surrounding topography, but it is at least necessary to add the citation or better to show a bathymetry map.
The source of the bathymetry data (UGRH, 2009) is given in Section 1.1 (P4L11-12) and again in Section 2 (P5L32-33). The lake bathymetry used in this model comes from a 2009 bathymetric survey done by the Peruvian Glaciology and Water Resources Unit (called UGRH from the name of the unit in Spanish). In lieu of showing a bathymetric map, we have decided to show the profile of the lake (Figure 2), as we believe this better communicates the topography of the lakebed. This is stated at the beginning of Section 2 (P5L32-33). However, we neglected to state the source of the topographic data. The topography of the surrounding terrain comes from Horizons (2013). We apologize for this oversight., and a reference has been added with the source of the topographic data used in this work.

P8 L29: this is inaccurate. At least some data we have from one event from March 19th 2003.
You are correct that we do have some data from the 2003 landslide. However, the data we have from this event are insufficient for model validation. The types of data that we have from previous events such as the 2003 landslide at Lake Palcacocha generally consist of estimates of the total slide volume and the run-up heights of the waves on the terminal and/or lateral moraines. We can see in the 3D simulations of avalanche-generated waves that are presented in this paper that the wave heights and run-up heights are very different. The theoretical run-up height against a vertical wall is twice the wave height, but in natural environments, the actual run-up height is highly dependent on the field characteristics (eg., lakebed geometry and moraine slope). Additionally, for many GLOF events, even the run-up height is not known with certainty. In many cases, only the minimum run-up height is known because overtopping of the damming moraine was observed, so it was concluded that the run-up height must have been greater than the freeboard.

In response to this comment and similar ones from other reviewers, we have added a few sentences to the manuscript to clarify what data are available from the 2003 landslide and why we cannot use that event to validate the model.

P31 L31-32: Sure, the discrepancy in volume estimation is a problem, but why should be difference in moraine-dammed and bedrock-dammed lake in the sense of dam overtopping. Please explain. The only difference I see is in the potential for moraine erosion during the overflow compared to the bedrock. (To be precise the Lake 513 has a small moraine on the top of the bedrock-dam.).
The authors could not find the text referred to by the reviewer. There is no page 31 in the manuscript.

P15 L37: Another sentence where the bathymetry map should be cited (or better included).
This reference has been added to the manuscript.

P 16 L18 This is OK for me, but there is probably one more issue which might be considered in the Discussion. Water will overtop the basal moraine first (you called them "small moraine") and

soon it will reach the breakthrough (from 1941) in the former frontal moraine, which is rather narrow for the fluent continuation of the flood wave. (This is another reason why the photo should be included – perhaps taken from the right lateral moraine, that the former outburst will be clear visible).
The potential erosion of the moraine was extensively considered in Somos-Valenauela et al (2016) and found to be negligible, and that analysis is not repeated here.

P16 L31 Please consider, that the current dam of the Palcacocha Lake is rather wide in the foundation, compared to the typical narrow and high moraines from some other lakes which could be rather easily eroded during the overflow (or outburst).
Consideration of the potential erosion of the damming-moraine is beyond the scope of this work. The potential erosion of the damming-moraine is discussed in Rivas et al. (2015) and Somos-Valenzuela et al. (2016). Somos-Valenzuela et al. (2016) determined that a breach of the damming-moraine due to erosion from the overtopping wave is very unlikely. This is for the reason that you mention in your comment: the high width-height ratio of the lake-damming moraine and the low slope of the distal face of the moraine (making it more stable).

P17 L19 Better to add the volumes for small and medium avalanches.
The avalanche volumes have been added to the manuscript.