Nat. Hazards Earth Syst. Sci. Discuss., 2, 5971–6002, 2014
www.nat-hazards-earth-syst-sci-discuss.net/2/5971/2014/
doi:10.5194/nhessd-2-5971-2014

Natural Hazards and Earth System Sciences
Discussions
Open Access

Predicting outflow induced by moraine failure in glacial lakes: the Lake Palcacocha case from an uncertainty perspective

D. S. Rivas, M. A. Somos-Valenzuela, D. C. McKinney, and B. R. Hodges

Center for Research in Water Resources, University of Texas at Austin, Austin, Texas, USA

Received: 8 August 2014 – Accepted: 6 September 2014 – Published: 19 September 2014

Correspondence to: D. C. McKinney (daene@aol.com)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Moraine dam collapse is one of the causes of Glacier Lake Outburst Floods. Available models seek to predict both moraine breach formation and lake outflow. The models depend on hydraulic, erosion, and geotechnical parameters that are mostly unknown or uncertain. This paper estimates the outflow hydrograph caused by a potential collapse of the moraine dam of Lake Palcacocha in Peru and quantifies the uncertainty of the results. The overall aim is to provide a simple and robust method of calculation of the expected outflow hydrographs that is useful for risk assessment studies. To estimate the peak outflow and failure time of the hydrograph, we assessed several available empirical equations based on lake and moraine geometries; each equation has defined confidence intervals for peak flow predictions. Complete outflow hydrographs for each peak flow condition were modeled using a hydraulic simulation model calibrated to meet the peak flows estimated with the empirical equations. Failure time and peak flow differences between the simulations and the corresponding empirical equations were used as error parameters. Along with an expected hydrograph, lower and upper bound hydrographs were calculated for Lake Palcacocha, representing the confidence interval of the results. The method has several advantages: first, it is simple and robust. Second, it evaluates the capability of empirical equations to reproduce the conditions of the lake and moraine dam. Third, this method accounts for uncertainty in the hydrographs estimations, which makes it appropriate for risk management studies.

1 Introduction

Flood risk downstream of a natural earthen dam depends on the capacity of the dam to hold the impounded water. That capacity can be exceeded due to overtopping wave events or catastrophic collapse of the dam induced by either structural failure or accelerating erosive processes. In moraine dammed glacier lakes, both kinds of failure can occur. Knowing a priori the hydrograph for a potential glacier lake outburst flood

(GLOF) would be useful for risk analysis and mitigation, but it is not clear the level of detail required to have a reasonable approximation. In this paper we consider methods for estimating the hydrograph for potential erosive failure of a moraine dammed glacial lake with structural failure being the limit of the most rapid erosive process.

The erosive physical phenomena that drive earth dam breaches are not fully understood. The complex interaction between soil and fluid dynamics that governs the dam erosion process presents a research challenge. Two types of methods have been previously developed to predict breach development across earthen dams and the resulting outflow hydrographs. The first type involves deterministic models that attempt to describe the governing physics of the problem and apply sediment transport or energy dissipation models (Temple et al., 2005; Hanson et al., 2005; Visser et al., 2010; Westoby et al., 2014). These models are focused on engineered earthen dams. Their utility is limited by our relatively poor understanding of the hydro-erosive phenomena and because we typically lack the data necessary to characterize the hydraulic and geological properties of natural dams. The second type of method involves empirical models based on recorded historical events of dam failures, which are used to estimate the characteristics of a dam breach and the resulting maximum peak flow. These methods use regression analysis to relate the peak outflow through the breach either to the depth or volume of water behind the dam, or to the product of these variables (Pierce et al., 2010; Wahl, 2010; Westoby et al., 2014). Empirical models can be used for cases where the characteristics of both impounded water volume and dam geometry are similar to those of the historical cases used to build the model. Their similarity requirement restricts their practical range of applications.

Deterministic models predict breach growth by considering hydrodynamic and sediment transport relationships inside coupled models that simulate dynamically varying weirs. These numerical models mostly use the Meyer-Peter and Muller (1948) sediment-transport relation to simulate forward erosion processes driving the breach shape and rate of growth. In contrast, field observations suggest that backward erosion, from the front-end of the dam to the dam crest, is an important process in dam breach formation, this backward erosion process is not addressed by sediment-transport models (Costa and Schuster, 1988; O'Connor et al., 2001; Temple et al., 2005). Furthermore, erosive breach mechanisms are inherently difficult to deterministically predict for glacier lake moraines as we lack detailed geotechnical data. The accuracy of sediment transport models to simulate breach growth processes has not been thoroughly demonstrated, nor has their advantage over simple parameterization of average erosion rates on the basis of empirical data (Walder and O'Connor, 1997). For example, in the case of Lake Palcacocha considered below, uncertainty and lack of data limits the information of the damming moraine. It follows that deterministic models of erosive breaches are still research tools that are not yet suitable for risk analysis and mitigation studies.

Given the obstacles to developing and applying deterministic models, empirical models represent a reasonable alternative to assess potential dam breach effects. However, to take advantage of their simplicity, we must assess their suitability. Although several authors propose empirical models and address uncertainty in dam breach estimations (Wahl, 2004; Xu and Zhang, 2009; Peng and Zhang, 2012), less attention has been given to set criteria to select one empirical model over another. Consequently, assessing whether a model fits the conditions of a particular dam site poses a challenge prior to effective model application.

Landslide dams, a particular case of natural dams, have received more attention than glacial moraine dams, producing, as a result, empirical estimation methods on peak outflow (Costa and Schuster, 1988; Wahl, 2004; Walder and O'Connor, 1997). The geologic processes behind the formation of each type of dam are different, but failure assessment methods might apply for both types due to common instability issues. Massive landslides commonly create dams after an almost instantaneous process of material deposition from rock and debris avalanches; rock and soil slumps; and debris, mud or earth flows (Costa and Schuster, 1988; Nicoletti and Parise, 2002; Parise et al., 2003). In contrast, glacial moraine dams take geologic time scales to emerge. Despite these formation differences, the resulting landslide or moraine dams

NHESSD
2, 5971–6002, 2014

Predicting outflow induced by moraine failure in glacial lakes

D. S. Rivas et al.

are similar in terms of the poorly consolidated and heterogeneous composing materials (Costa and Schuster, 1988). Although landslide dams are highly unstable, showing life spans even shorter than one year, better graded debris flows favor longer longevities, with overtopping triggering most of their failures (Costa and Schuster, 1988; Nicoletti and Parise, 2002).

Hydraulic simulation models such as DAMBRK (Fread, 1984) can complement the empirical breach equations. The fixed geometry and dynamic conditions of the dam break problem (lake volume, breach shape, and failure time) limit the possible hydrographs resulting from a hypothetical dam breach. These hydrographs, which reflects the breach drainage capacity, are different for each possible setting of lake, dam, and breach geometry. The problem is that, even though the drainage capacity can be estimated in a simplified way by hydraulic simulation models such as DAMBRK, these models lack capability to self-determine the breaching parameters. On the other hand, empirical equations do estimate breach development parameters, but they are based on historical observations not directly related to the problem of interest. Thus, empirical models are not capable of determining the hydraulic conveying capacity of the analyzed breach.

The principal contention of this paper is that a simple empirical method combined with hydraulic simulations can be used for estimating potential dam break hydrographs for moraine-dammed glacial lakes, despite our admittedly limited knowledge of erosive processes leading to dam failure. The fundamental problem is that existing empirical models (which typically require only water depth and impounded volume as input parameters) only provide outputs of peak outflow and failure time, i.e., they cannot produce a hydrograph for risk planning and management. For this purpose, failure time, or breach formation time, is the time needed for complete development of the ultimate breach from the initial breakthrough at the crest to the end of significant lateral enlargement (Froehlich, 2008). In contrast, hydraulic simulation models can provide the full outflow hydrographs but require more extensive site-specific geometric data and calibration. Herein, we assess the application of empirical models as a calibration tool for hydraulic simulations generating a hydrograph for natural dam-break problems. The method, applied to nine empirical dam-breach models, evaluates the case of a single natural glacier lake dam, estimating outflow hydrograph predictions and uncertainties (Wahl, 2004; Xu and Zhang, 2009; Peng and Zhang, 2012) to choose the most robust model. In addition, from the uncertainty bands of the empirical models we compute the upper and lower of potential outflow hydrographs instead of a single expected instance, providing more robust results for flood risk management studies. We propose that the best empirical model for a given site produces results that best match those of hydraulic simulations. The site used here is Lake Palcacocha in Peru, a glacier lake impounded by a moraine dam, for which lower bound, predicted value, and upper bound outflow hydrographs are estimated considering the prediction intervals of the empirical breaching models.

2 Methodology

2.1 Overview

In a moraine dam failure, the outflow hydrograph depends on the stored water volume along with the breach geometry and growth rate. For an erosive failure, the expanding rate and shape of the breach (relative to the water level) are the principal hydrographical controls. We combine empirical models and hydraulic simulations to overcome some of the limitations imposed by both the lack of knowledge of the breach formation processes and the moraine characteristics. The method involves three steps: (1) peak flow and failure time estimation using empirical models, (2) calibration of a hydraulic simulation of the moraine breaching process using site-specific geometrical data and empirical model results, and (3) model selection and uncertainty band assessment to define expected, upper and lower bound hydrographs of the breach outflow.

2.2 Peak flow and failure time estimation

The literature provides empirical models derived for different dam failure events across the world. These models are useful to define the characteristics of potential breach outflow when accurate data about dam/moraine physical conditions are not available. Nine empirical models applicable to engineered and natural dam failures are provided in Table 1. Each model provides an estimate of failure time, and peak flow with the principal input data of water depth (from the initial lake free surface to the final breach), and impounded volume above the final breach. The more complex models require estimates of "erodability" of the dam, classified as low/medium/high. Several models also require an estimate of the breach volume as an input. These depth and volume data can be derived from digital bathymetry and terrain models once a potential breach shape is defined.

Breach dimensions, however, are important sources of uncertainty. Practical criteria to define potential breach shapes include considering the dam might completely collapses. Even though the breach shape can vary in terms of nature, magnitude and continuity of the trigger mechanism (avalanche generated wave overtopping, over storage, extreme rainfall events, etc.), "...the worst case event is the most appropriate design analysis for planning possible mitigating measures" (Laenen et al., 1987).

2.3 Dam breach hydraulic simulation

Dam breach numerical simulations can be created using the US National Weather Service (NWS) DAMBRK dam-breach method (Fread, 1984). Extensive descriptions of the mathematical basis of DAMBRK can be found in Fread (1984, 1988, 1994). DAMBRK simulates the breach outflow process as an idealized hydraulic process; i.e., one-dimensional (1-D) open-channel flow over a broad-crested weir that linearly evolves with time (Wahl, 2004; Wurbs, 1987; DHI, 2008). This approach excludes erosion physics, and hence does not require geotechnical or structural parameters. A major disadvantage is the assumption of regular breach shapes and linear growth (Wurbs, 1987), which oversimplifies breach development in heterogeneous materials such as moraines. The DAMBRK breach development is not based on erosive processes and the user must define it as part of the input data. The definition includes both the maximum breach dimensions and the time to failure (i.e., to maximum breach).

In a DAMBRK simulation, the breach starts at the crest of the dam/moraine and grows in both directions vertical and horizontal, deepening and widening the breach shape. During each time step of a DAMBRK simulation, the discharge and energy head vary in according to water level, available volume, and the breach (weir) dimensions. The parameters used in the moraine breach model are: impounded lake geometry, surrounding terrain topography, breach shape, and failure times; the basic physical parameters are the same applied to the empirical models described in the previous section, including the elevation-volume curve, but are used in greater site-specific detail within DAMBRK rather than integrated to simple height and volume values as used in empirical models.

2.4 Assessment of empirical equation performance

For most potentially dangerous glacial lakes, there is little (if any) data to calibrate hydraulic simulations, and essentially no independent data sets for validation. Herein, we propose using the empirical models to provide estimates of the peak flow rate and failure time for calibration of DAMBRK. The failure time from a given empirical model is used with DAMBRK as a first estimate of the failure time input data. The simulation is run and the peak flow of the resulting hydrograph is compared to the peak flow of the empirical model. The DAMBRK input failure time is then adjusted in successive calibration runs until the peak flows of the simulation and empirical model are approximately matched. The difference between the failure time from the calibrated simulation and the failure time of the empirical model is used to assess the quality of the different empirical models and select the hydrographs that can be considered the most robust estimate of a potential dam breach.

For these comparisons, it is useful to define a normalized flow difference (Q_d) from the peak flow of the empirical model (Q_{pE}) and the peak flow of the hydraulic simulation (Q_{pH}) as

$$Q_d = \frac{\left|Q_{pE} - Q_{pH}\right|}{Q_{pE}} \times 100\,\% \qquad (1)$$

where the calibration is considered adequate when $Q_d < 2\,\%$. The empirical model performance is governed by a similar normalized time difference of

$$t_d = \frac{|t_{fE} - t_{fH}|}{t_{fE}} \times 100\,\% \qquad (2)$$

where t_{fE} and t_{fH} are the failure times for the empirical and the hydraulic simulation models, respectively. As Q_d is used for judging calibration, the resulting t_d is used to assess model performance.

2.5 Model selection and probabilistic assessment

Each empirical equation has an uncertainty band resulting from the residuals of the underlying regression model. The uncertainty bandwidth of the breaching parameters (i.e., the range between lower and upper bounds of predictions) reflects the likely variability for each model's predictions of peak flow. Wahl (2004), Xu and Zhang (2009), and Peng and Zhang (2012) developed analysis methods for uncertainty bands. The empirical models of Table 1 have the mean prediction error ($\overline{e}$), and standard deviation of the error (Se) as shown in Table 2. The $\overline{e}$ are the number of log cycles separating predicted and observed peak flows in the individual case studies compiled by each author. The sign of $\overline{e}$ indicates over or underestimation of peak outflows (Wahl, 2004). With the exception of the Froehlich model (Froehlich, 1995), all empirical models tend to overestimate peak outflows. This trend is consistent with prevailing conservative approaches of dam-break prediction and the adoption of worst-case scenarios in flood risk studies (Laenen et al., 1987). We apply a prediction interval as the expected lower (Q_l) and upper (Q_u) bounds on the peak outflow as plus or minus two standard deviations from the mean error, i.e.,

$$\{Q_\mathrm{l}, Q_\mathrm{u}\} = \left\{Q_\mathrm{p} \times 10^{-\bar{e}-2\mathrm{Se}}, Q_\mathrm{p} \times 10^{-\bar{e}+2\mathrm{Se}}\right\} \tag{3}$$

where Q_p is the predicted outflow. Comparison of the prediction interval for the empirical models is provided in Table 2. The prediction interval is an inherent characteristic of each empirical model or, to be more precise, it is a characteristic of each model when compared with actual values of the original sample of dam breaks used in the regression.

We can use the prediction interval values to estimate the range of hydrographs expected for a hydraulic simulation calibrated with a particular empirical model. That is, we can adjust the failure time of the hydraulic simulation in successive runs to match the Q_l and Q_u, obtaining hydrographs that are the expected range of a potential dam break.

2.6 Study area

Lake Palcacocha and similar glacier lakes have emerged as a consequence of deglaciation processes occurring in the Cordillera Blanca region in Peru (Figs. 1 and 2). Climate change in recent decades has accelerated glacier retreat and hence lake growth in this area (UGRH, 2010; Burns and Nolin, 2014). For instance, the volume of Lake Palcacocha increased from $0.5 \times 10^6\,\mathrm{m}^3$ in 1947 to $17 \times 10^6\,\mathrm{m}^3$ in 2009 (Instituto Nacional de Defensa Civil, 2011). A Glacier Lake Outburst Flood (GLOF) occurred from Lake Palcacocha in 1941 – when the lake volume was about $12 \times 10^6\,\mathrm{m}^3$. The recent increase in lake volume raises concerns on a persistent risk of flood for the downstream city of Huaraz. The three conditions (sustained lake growth, recent disaster antecedents, and unstable damming conditions) reinforce concerns about Lake Palcacocha as a threat for the Huaraz population, and furthermore, demand practical and applicable ways to predict potential moraine failures and water discharges from the lake.

The Cordillera Blanca, located approximately 180 km from the Peruvian coast where the Nazca plate dips below the South American continental plate, is a relatively recent granodioritic batholithic intrusion into folded and faulted Mesozoic marine sediments (Young and Lipton, 2006; Mark, 2008; Sevinc, 2009). Large-scale uplift produced the current Cordillera Blanca and Cordillera Negra ranges with the Callejón de Huaylas in between them forming the Rio Santa Basin. The Cojup valley is a typical glacial valley with very strong recent fluvial remodeling and comprises various types of intrusive rocks, such as granites and granodiorites with free rock faces above the talus deposits supplying the valley bottom with huge boulders (Vilimek et al., 2005). Lake Palcacocha is dammed by a moraine composed of rock and debris deposits left behind by the retreat of the contributing glaciers. There are few geological studies of the current composition of the moraine, but the breach opened by the 1941 GLOF event suggests that a large portion of the moraine is composed of loose, non-cohesive, and unconsolidated material.

Lacking the precise geotechnical and erodability characteristics of the Lake Palcacocha moraine, two main criteria were used to define the potential shape and depth of the breach. First, we assume that the easiest path for water to flow through will be the path defined by the 1941 GLOF. That breach still exists, and it seems likely that a new breach would begin by eroding the old one. Second, in the case of Lake Palcacocha the worst-case breach depth is the full depth of the moraine. Absence of bedrock and the prevailing presence of poor cohesion materials are likely in the Lake's moraine; such conditions might lead to formation of large-scale breaches.

The profile of the Lake Palcacocha moraine (Fig. 3) exhibits three elevation layers associated with different moraine dimensions and impounded water volumes. The surface of the upper layer (0 to 22.5 m depth) is more susceptible to erosion because it is immediately exposed to water flow; the degree of compaction and cohesion of these shallowest moraine layers is also likely to be lower than that of deeper layers. To reach the bottom of the second layer, a breach must go as deep as 56 m, longitudinally erode over 900 m of moraine material, and be able to drain $16.9 \times 10^6\ m^3$ of water. The likelihood of such an event is unclear, but uncertainty of the internal moraine structure does not allow us to reject the possibility of a massive breach. Therefore, we consider the breach depth represented by the second layer in Fig. 3 (56 m) to be the worst-case scenario. The third layer is constituted by a small volume ($0.8 \times 10^6\ m^3$), which accounts for the remaining 5 % of the entire water volume. To release that volume, water flow must erode over 1600 m of moraine material, extending the breach 615 m longer than the length developed in the second layer. Thus, the water volume held in the bottom layer is unlikely to be drained with any rapidity because the long breach length required at that depth, and low available potential energy (2.6 % of the total potential energy of the lake) indicates the erosion time would be relatively long.

Discharge from the moraine will progressively enlarge the downstream channel until the breach intersects the bottom of the second layer. By considering moraine erosion as a backward process (moving from the downstream face to the upstream face of the moraine), the shape of the potential breach (Fig. 4a) will reach its maximum lateral extension at the breached-channel segments close to the front toe of the moraine prior to extending backward along the whole channel. The maximum breach has a bottom width of 50 m, slopes of 1 : 1 vertical to horizontal, and a depth of 56 m. The bottom width of the breach and downstream channel are approximately equal at the lowest elevation of the second layer. This shape will propagate backwards forming the breach channel (Fig. 4b) as a deeper extension of the 1941 GLOF channel (overlaid cross sections represented by dashed lines in Fig. 4b).

Lake Palcacocha bathymetry measurements made in 2009 (UGRH, 2010) allow us to determine a volume/elevation curve for the lake (Fig. 5). The curve represents the impounded water volume as water depth increases. The parameters resulting from combining the estimated maximum potential breach shape, lake geometry and surrounding digital terrain model are shown in Table 3. These are the inputs required by the empirical models to estimate peak outflow and failure time for the moraine breach process. The impounded water volume in Table 3 accounts for the volume of water that can be drained through the two breaches mentioned in the table; thus, neglecting the water in the upper 8 m below the crest of the moraine because existing drainage structures prevent the lake from exceeding that level.

3 Results and discussion

3.1 Comparison of empirical models

Each empirical model assigns different coefficients and functional forms to the input data (see Table 1), which provides different relationships for flow-depth and flow-volume. Figure 6 presents variations in the peak flow (Q_p) estimated by a subset of empirical models as a function of water volume, V_w (Fig. 6a) and water depth, H_w (Fig. 6b). The slopes in Fig. 6 reflect the weights each model assigns to V_w and H_w as predictors of Q_p. As indicated in Fig. 6a, a simple model such as USBR (1982) is insensitive to changes in V_w since the model does not include that parameter. Although there are scale differences, models such as Froehlich (1995), Xu and Zhang-simple (Xu and Zhang, 2009), Peng and Zhang-simple and -full (Peng and Zhang, 2012) show similar responses to V_w variations. On the contrary, Xu and Zhang-full (Xu and Zhang, 2009), the only model that accounts for volume of eroded material, is more sensitive to variations in V_w. Figure 6a also suggests that, in general, empirical equations are more sensitive to changes in V_w at lower volumes.

Figure 6b shows three trends in the behavior of Q_p as H_w increases. First, the Xu and Zhang-full (Xu and Zhang, 2009) and USBR (1982) models weight H_w more heavily as a predictor of Q_p, but there is a transition point (H_w = 55 m) where the effect of H_w changes are more evident (higher slope) in the USBR (1982) model, leading to higher differences between the predictions of these models. Second, the Froehlich (1995) and Xu and Zhang-simple (Xu and Zhang, 2009) models present moderate and more constant slopes, indicating that the influence of H_w is less pronounced than in the

NHESSD
2, 5971–6002, 2014

first group. Third the Peng and Zhang-full (Peng and Zhang, 2012) and McDonald and Landridge-Monopolis (1984) models have almost horizontal slopes indicating that they are less sensitive to changes in H_w.

3.2 Comparison of empirical and DAMBRK model results

Table 4 summarizes the peak flow and failure time results for the empirical models listed in Table 1 and the DAMBRK models considering a Lake Palcacocha moraine breach. The range of normalized peak flow difference (Q_d) is 0.04–1.84 % with a median value of 0.47 %. These low values are the result of Q_d being matched during calibration. The range of the normalized failure time difference (t_d) is 19.6–96.8 % with a median of 71.6 %. The results suggest that, in this case, the Froehlich (1995) model performs better than the other models because the t_d = 19.6 %, which is the smallest for the 14 models. The simplicity of the Froehlich (1995) model reduces the prediction uncertainty that is implicitly added by erodability conditions in other models such as Xu and Zhang (2009), Peng and Zhang (2012), or McDonald and Landridge-Monopolis (1984), for which the normalized differences of time failure are over 90 %. More complex models that incorporate erosion parameters to estimate breach formation and peak outflow might become more relevant in cases where the erosion parameters are better known. However, additional erodability parameters seem to bring additional uncertainty in the case of Lake Palcacocha, where the geotechnical characteristics of the moraine are mostly unknown.

The hydraulic simulation completes a second function. Besides measuring the capability of the best performing empirical model to provide reasonable outflow estimations, it produces full outflow hydrographs for the expected breach and the corresponding lower and upper uncertainty bounds. Figure 7 shows the range of hydrographs generated using DAMBRK to simulating the discharge of a 56 m-depth breach in the frontal moraine of Lake Palcacocha.

NHESSD
2, 5971–6002, 2014

3.3 Limitations and advantages

The method presented here is inherently limited. The criteria used to compare the models are relative; that is, we consider one empirical model performs better than another one if its predicted peak flow can be used to obtain to a smaller difference between its predicted time to failure and the time to failure computed with the hydraulic simulation. We can find no obvious thresholds for judging what difference levels are significant in an absolute sense. Furthermore, the method relies on the hydraulic simulation providing a reasonable representation of the outflow hydrograph. If the simplification of the hydraulic simulation is inappropriate, the resulting analysis of the empirical models is invalid. Finally, we note that the preferred empirical model in this study, Froehlich (1995), is only for the Lake Palcacocha and results cannot be generalized to other lakes. Because the lake and dam geometry affect the hydraulic simulation of the dam break, it is entirely possible that a different lake/dam would produce hydrographs better matching a different empirical equation.

The main advantages of this method reside in its simplicity and robustness, making it useful in situations where data are sparse, such as in the analysis of the risk of glacial lakes. The method takes a step beyond the previous empirical models and by providing a method to estimate a dam-break hydrograph that could be used for more effective modeling of potential downstream consequences. Another advantage emerges from further applying the results to empowering risk assessment or vulnerability studies. Focusing more specifically on the Froehlich empirical models (Froehlich, 1995), Table 5 shows the mean prediction errors for failure time and peak discharge, the width of the uncertainty bands, and the prediction interval for a hypothetical predicted value of 1 using Froehlich's equations (Wahl, 2004). Table 6 shows the predicted peak outflow and failure time estimated by Froehlich (1995) empirical model and hydraulic simulation and the associated prediction intervals (upper and lower bounds) for Lake Palcacocha conditions. The hydrographs in Fig. 7 present an outflow event and the lower and upper bounds for a 56 m breach from Lake Palcacocha. Instead of providing a single outflow

NHESSD
2, 5971–6002, 2014

result, this approach allows risk studies to take into account a range of possible events accounting for the uncertainty in the breaching calculations.

4 Conclusions

A new method has been presented for extending prior empirical models that provide only peak flows and failure times for a dam break. Using the new method, it is possible to determine the maximum and minimum flow hydrographs that are consistent with the empirical model. The new method evaluates existing empirical models to find the best match to the hydrograph produced by calibrating a hydraulic simulation. In the present study, the DAMBRK model was used, but the method could be adapted to any unsteady-flow hydraulic simulation method. The advantage of the method is that it provides a simple approach to estimating a hydrograph for potential dam breaks where data are limited, which is the case for many glacier lakes that endanger downstream populations.

The method succeeds on providing first hydrograph estimations that can support risk assessment studies in remote locations. Likewise, it sets criteria to evaluate the quality of those estimations. However, application of the method to detailed dam break studies, which require less uncertainty, remains limited due to lack of precise validation data. Furthermore, the inner nature of the applied empirical models, built upon specific sets of historical cases, limits the range of locations where the models are reliable, which prevents us from applying the method in a generalized way. Rather, the method requires careful judgment in evaluating model performances trough normalized differences of time failures.

The new method was demonstrated in estimating the hydrographs for potential breaches in a moraine dammed glacier lake (Lake Palcacocha, Peru). The best results were obtained using the Froehlich (1995) empirical model, with an error of 19.6 % in failure time. Uncertainty of predicted outflows and corresponding hydrographs are computed for every empirical model studied. Using the method, we were able to predict expected outflow hydrographs and their uncertainty range (lower and upper bound hydrographs).

Acknowledgements. The authors acknowledge the support of the USAID Climate Change Resilient Development (CCRD) project and the Fulbright Foundation for the support of Rivas and Somos-Valenzuela. Hodges was partially supported by National Science Foundation under Grant No. CCF-1331610.

References

Burns, P. and Nolin, A.: Using atmospherically-corrected Landsat imagery to measure glacier area change in the Cordillera Blanca, Peru from 1987 to 2010, Remote Sens. Environ., 140, 165–178, doi:10.1016/j.rse.2013.08.026, 2014.

Costa, J. E. and Schuster, R. L.: The formation and failure of natural dams, Geol. Soc. Am. Bull., 100, 1054–1068, 1988.

DHI – Danish Hydraulic Institute: A Modelling System for Rivers and Channels, Copenhagen, 2008.

Fread, D. L.: DAMBRK: the NWS Dam-Break Flood Forecasting Model, National Weather Service, Office of Hydrology, Silver Spring, MD, 1984.

Fread, D. L.: DAMBRK: The NWS DAMBRK Model: Theoretical Background/User Documentation, Hydrologic Research Laboratory, National Weather Service, Office of Hydrology, Silver Spring, MD, 1988.

Fread, D. L.: NWS FLDWAV Model: The Replacement of DAMBRK for Dam-Break Flood Prediction, Hydrologic Research Laboratory, National Weather Service, Office of Hydrology, Silver Spring, MD, 1994.

Froehlich, D. C.: Peak outflow from breached embankment dam, J. Water Res. Pl.-ASCE, 121, 90–97, 1995.

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

Hanson, G. J., Temple, D. M., Morris, M., Hassan, M., and Cook, K.: Simplified breach analysis model for homogeneous embankments: Part II, parameter inputs and variable scale model comparisons, in: Proceedings of 2005 US Society on Dams Annual Meeting and Conference, Salt Lake City, 151–161, 2005.

Instituto Nacional de Defensa Civil: Informe de peligro No. 003-12/05/2011/COEN-SINADECI/15:00 horas (Informe No. 01): Peligro por aluvión en el departamento de Ancash, Huaraz-Peru, COEN-SINADECI, 2011.
Laenen, A., Scott, K. M., Costa, J. E., and Orzol, L.: Hydrologic Hazards Along Squaw Creek From a Hypothetical Failure of the Glacial Moraine Impounding Carver Lake Near Sisters, Oregon, US Geological Survey Open File Report 87–41, US Geological Survey, Portland, Oregon, 48 pp., 1987.
Mark, B. G.: Tracing tropical Andean glaciers over space and time: some lessons and transdisciplinary implications, Global Planet. Change, 60, 101–114, 2008.
McDonald, T. C. and Langridge-Monopolis, J.: Breaching characteristics of dam failures, J. Hydraul. Eng.-ASCE, 110, 567–586, 1984.
Meyer-Peter, E. and Müller, R.: Formulas for bed-load transport, Proc., 2nd Meeting, IAHR, Stockholm, Sweden, 39–64, 1948.
Nicoletti, P. G. and Parise, M.: Seven landslides dams of old seismic origin in southeastern Sicily (Italy), Geomorphology, 46, 203–222, 2002.
O'Connor, J. E., Hardison III, J. H., and Costa, J. E.: Debris Flows from Failures of Neoglacial-Age Moraine Dams in the Three Sisters and Mount Jefferson Wilderness Areas, Oregon, US Geological Survey Professional Paper 1606, US Geological Survey, Reston VA, 93 pp., 2001.
Parise, M.: Observation of surface features on an active landslide, and implications for understanding its history of movement, Nat. Hazards Earth Syst. Sci., 3, 569–580, doi:10.5194/nhess-3-569-2003, 2003.
Parise, M., Coe, J. A., Savage, W. Z., and Varnes, D. J.: The Slumgullion landslide (southwestern Colorado, USA): investigation and monitoring, in: Proc. International Workshop "Occurrence and mechanisms of flow-like landslides in natural slopes and earthfills", edited by: Picarelli, L., 253–263, 2003.
Peng, M. and Zhang, L. M.: Breaching parameters of landslide dams, Landslides, 9, 13–31, 2012.
Pierce, M. W. and Thornton, C. I.: Predicting Peak Outflow from Breached Embankment Dams, Colorado State University, Fort Collins, Colorado, 45 pp., 2010.
Sevinc, J.: The Cordillera Blanca Guide: a Unique Landscape Explained + Trips, University of Amsterdam, the Netherlands and The Mountain Institute, Lima, 212 pp., 2009.

NHESSD
2, 5971–6002, 2014

Predicting outflow induced by moraine failure in glacial lakes

D. S. Rivas et al.

Temple, D. M., Hanson, G. J., Neilsen, M. L., and Cook, K.: Simplified breach analysis model, Part I: Background and model components, Proc. 2005 US Society on Dams Annual Meeting and Conference, Denver, CO, 151–161, 2005.

UGRH – Unidad de Glaciologia y Recursos Hidricos: Area de Inventario de Glaciares y Lagunas, Autoridad nacional del Agua, Direcccion de Conservacion y Planeamiento de Recursos Hidricos, Huaraz, Peru, 2010.

USBR – US Bureau of Reclamation: Guidelines For Defining Inundated Areas Downstream From Bureau of Reclamation Dams, Reclamation Planning Instruction 82-11, Water Resources Research Laboratory, Denver, CO, 1982.

Vilímek, V., Zapata, M. L., Klimes, J., Patzelt, Z., and Santillan, N.: Influence of glacial retreat on natural hazards of the Palcacocha Lake area, Peru, Landslides, 2, 107–115, doi:10.1007/s10346-005-0052-6, 2005.

Visser, K., Hanson, G. J., Temple, D. M., Lobrecht, M., Neilsen, M. L., Funderburk, T., and Moody, H.: WinDam B Earthen Embankment Overtopping Analysis Software, US Natural Resources Conservation Service, US Department of Agriculture, Washington, D.C., 2010.

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

Wahl, T. L.: Dam Breach Modeling – An Overview Of Analysis Methods, US Bureau of Reclamation, Water Resources Research Laboratory, Denver, CO, 2010.

Walder, J. S. and O'Connor, J. E.: Methods for predicting peak discharge of floods caused by failure of natural and constructed earthen dams, Water Resour. Res., 33, 2337–2348, 1997.

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

Wurbs, R. A.: Dam-breach flood wave models, J. Hydraul. Eng.-ASCE, 113, 29–46, 1987.

Xu, Y. and Zhang, L.: Breaching parameters for earth and rockfill dams, J. Geotech. Geoenviron., 135, 1957–1970, 2009.

Young, K. R. and Lipton, J. K.: Adaptive governance and climate change in the tropical highlands of western South America, Climatic Change, 78, 63–102, doi:10.1007/s10584-006-9091-9, 2006.

NHESSD

2, 5971–6002, 2014

Predicting outflow induced by moraine failure in glacial lakes

D. S. Rivas et al.

Table 1. Empirical equations for peak flow and failure time for dam breach events.

	Reference	Peak flow, Q_p ($m^3 s^{-1}$)	Failure time, t_f (h)
1	Froehlich (1995)	$0.607\left(V_w^{0.295} H_w^{1.24}\right)$	$0.00254\left(V_w^{0.53} H_w^{-0.9}\right)$
2	USBR (1982)	$19.1 H_w^{1.85}$	$0.011\left(B_{avg}\right)$; $B_{avg} = 3H_w$
3	Xu and Zhang (2009) (simple)	$\left(9.80665 V_w^{5/3}\right)^{0.5} \times 0.133\left(\frac{V_w^{1/3}}{H_w}\right)^{-1.276} e^a$; High erodability: $a = -1.321$ Med erodability: $a = -1.73$ Low erodability: $a = -0.201$	$b\left(\frac{H_w}{15}\right)^{0.634}\left(\frac{V_w^{1/3}}{H_w}\right)^{1.246}$; High erodability: $b = 0.038$ Med erodability: $b = 0.066$ Low erodability: $b = 0.205$
4	Xu and Zhang (2009) (full)	$\left(9.80665 V_w^{5/3}\right)^{0.5} \times 0.175\left(\frac{H_w}{15}\right)^{0.199}\left(\frac{V_w^{1/3}}{H_w}\right)^{-1.274} e^a$; High erodability: $a = -0.705$ Med erodability: $a = -1.039$	$0.304\left(\frac{H_w}{15}\right)^{0.634} \times \left(\frac{V_w^{1/3}}{H_w}\right)^{1.228} e^b$; High erodability: $b = -1.205$ Med erodability: $b = -0.564$
5	Peng and Zhang (2012) (simple)	$9.80665^{0.5} \times H_w^{1.129}\left(\frac{V_w^{1/3}}{H_w}\right)^{1.536} e^a$; High erodability: $a = 1.236$ Med erodability: $a = -0.38$ Low erodability: $a = -1.615$	$H_w^{0.293}\left(\frac{V_w^{1/3}}{H_w}\right)^{0.723} e^b$; High erodability: $b = -0.805$ Med erodability: $b = -0.674$ Low erodability: $b = 0.205$
6	Peng and Zhang (2012) (full)	$9.8065^{0.5} \times H_w^{1.083}\left(\frac{H_w}{V_m}\right)^{-0.265}\left(\frac{V_m^{1/3}}{H_w}\right)^{-0.471}\left(\frac{V_w^{1/3}}{H_w}\right)^{1.569} e^a$; High erodability: $a = 1.276$ Med erodability: $a = -0.336$ Low erodability: $a = -1.532$	$H_w^{0.293}\left(\frac{H_w}{V_m}\right)^{-0.024}\left(\frac{V_m^{1/3}}{H_w}\right)^{-0.103}\left(\frac{V_w^{1/3}}{H_w}\right)^{0.705} e^b$; High erodability: $b = -0.635$ Med erodability: $b = -0.0518$
7	McDonald and Landridge-Monopolis (1984)	$1.154(V_w \times H_w)^{0.412}$	$0.0179 V_m^{0.364}$
8	McDonald and Landridge-Monopolis (1984) (envelope)	$3.85(V_w \times H_w)^{0.411}$	$0.0179 V_m^{0.364}$
9	Walder and O'Connor (1997)	$1.51\left(g^{1/2} H_d^{5/2}\right)^{0.06}\left(\frac{kV_w}{g^{1/2} H_d^{1/2}}\right)^{0.94}$, for $\eta \ll 1$ $\eta = \frac{kV_o}{g^{1/2} H_d^{7/2}}$ Only the case for $\eta \ll 1$ is presented here (for relatively slow breach formation). For other cases see Walder and O'Connor (1997)	$\frac{H_d}{k}$

Note: H_w is water depth (m); V_w is water volume (m^3); V_m is moraine breach volume (m^3); a, b are erodability weighting coefficients; η is a erodability parameter; and k is the mean erosion rate of the breach ($m\,s^{-1}$), based on historical events from Walder and O'Connor (1997).

Table 2. Uncertainty estimates for peak flow predictions using empirical models (adapted from Wahl, 2004; Xu and Zhang, 2009; and Peng and Zhang, 2012).

Author	Number of case studies	Mean prediction error, $\overline{e}$ (log cycles)	Width of uncertainty band, ±2Se (log cycles)	Prediction interval around hypothetical predicted value of 1
Froehlich (1995)	32	−0.04	±0.32	0.53–2.3
USBR (1982)	38	+0.19	±0.50	0.2–2.1
Xu and Zhang (2009) (simple)	14	–	±0.48	0.33–3.01
Xu and Zhang (2009) (full)	14	–	±0.52	0.30–3.35
Peng and Zhang (2012) (simple)	41	–	±0.48	0.33–3.03
Peng and Zhang (2012) (full)	41	–	±0.47	0.34–2.9
McDonald and Landridge-Monopolis (1984)	37	+0.13	±0.70	0.15–3.7
McDonald and Landridge-Monopolis (1984) (envelope)	37	+0.64	±0.70	0.05–1.10
Walder and O'Connor (1997)	22	+0.13	±0.68	0.16–3.60

Table 3. Physical parameters for moraine breach models.

Parameter	Maximum breach
Depth of water (H_w)	49.7 m
Depth of the breach (H_d)	56.0 m
Volume of impounded water not including the lower zone (V_w)	16.9×10^6 m^3
Volume of moraine breach (V_m)	3.65×10^6 m^3
Bottom width (m)	50.0 m
Breach slopes	1 : 1 horizontal to vertical

NHESSD
2, 5971–6002, 2014

NHESSD
2, 5971–6002, 2014

Predicting outflow induced by moraine failure in glacial lakes

D. S. Rivas et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◂ | ▸
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Table 4. Peak outflow (calibrated) and breach failure time (result) estimated by empirical models and hydraulic simulation for Lake Palcacocha.

#	Reference	Erodability condition	Empirical models Peak flow Q_{pE} ($m^3\,s^{-1}$)	Empirical models Failure time t_{fE} (h)	Hydraulic simulation Peak flow Q_{pH} ($m^3\,s^{-1}$)	Hydraulic simulation Failure time t_{fH} (h)	Normalized difference Flow Q_d (%)	Normalized difference Time t_d (%)
1	Froehlich (1995)		10 426	0.51	10 412	0.61	0.14	19.62
2	Bureau of Reclamation		26 260	1.64	26 659	0.15	1.52	91.11
3a	Xu and Zhang (2009) (simple)	Med	9567	1.09	9556	0.68	0.11	37.45
3b	Xu and Zhang (2009) (simple)	High	14 401	0.63	14 306	0.43	0.66	31.27
3c	Xu and Zhang (2009) (simple)	Low	3756	3.38	3825	1.85	1.84	45.34
4a	Xu and Zhang (2009) (full)	Med	32 953	3.02	32 727	0.10	0.69	96.78
4b	Xu and Zhang (2009) (full)	High	44 674	1.59	44 624	0.05	0.11	96.77
5a	Peng and Zhang (2012) (simple)	Med	2186	5.24	2212	3.33	1.18	36.36
5b	Peng and Zhang (2012) (simple)	High	11 002	4.59	11 007	0.58	0.04	87.30
6a	Peng and Zhang (2012) (full)	Med	2533	9.03	2504	2.92	1.16	67.72
6b	Peng and Zhang (2012) (full)	High	12 699	5.04	12 664	0.50	0.27	90.08
7	McDonald and Landridge-Monopolis (1984)		5469	4.38	5369	1.28	1.83	70.83
8	McDonald and Landridge-Monopolis (1984) (envelope)		17 876	4.38	17 897	0.32	0.12	92.71
9	Walder and O'Connor (1997)		20 246	0.95	20 271	0.26	0.12	72.40
						Min	0.04	19.62
						Max	1.84	96.78
						Median	0.47	71.61

Table 5. Mean prediction errors for failure time and peak flow, width of uncertainty bands, and prediction interval (for hypothetical value of 1) using Froehlich's equations (Wahl, 2004).

Parameter	Mean Prediction Error (log cycles)	Width of Uncertainty Band (±2Se) (log cycles)	Prediction interval around hypothetical predicted value of 1
Failure Time	−0.22	±0.64	0.38–7.30
Peak Discharge	−0.04	±0.32	0.53–2.30

NHESSD
2, 5971–6002, 2014

Table 6. Predicted peak outflow and failure time estimated by Froehlich's empirical models and hydraulic simulation and the associated prediction intervals (upper and lower bounds) for Lake Palcacocha conditions.

Parameter	Empirical model		Hydraulic simulation		Normalized differences	
	Q_{pE} ($m^3 s^{-1}$)	t_{fE} (h)	Q_{pH} ($m^3 s^{-1}$)	t_{fH} (h)	Q_d (%)	t_d (%)
Lower bound	5526	3.72	5533	1.24	0.13	66.69
Predicted value	10 426	0.51	10 412	0.61	0.13	19.61
Upper bound	23 980	0.19	24 016	0.19	0.15	1.96

NHESSD
2, 5971–6002, 2014

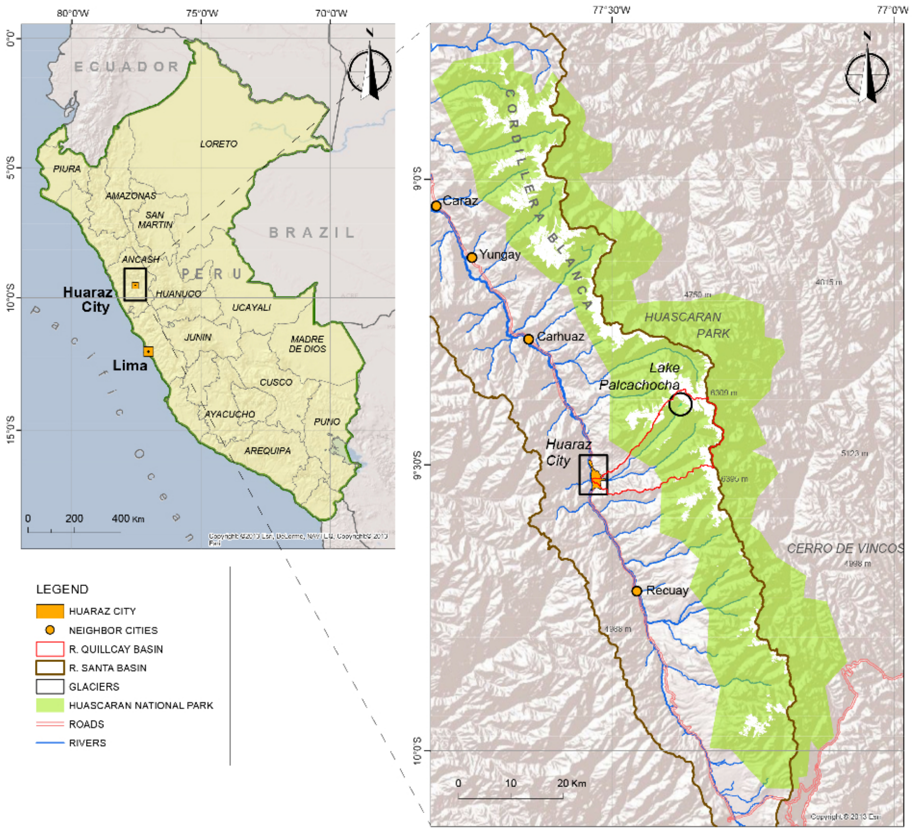

Figure 1. Lake Palcacocha location, upstream from Huaraz City in the Cordillera Blanca in Peru.

Figure 2. Front views of Lake Palcacocha and the breach of the 1941 GLOF.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

NHESSD

2, 5971–6002, 2014

Predicting outflow induced by moraine failure in glacial lakes

D. S. Rivas et al.

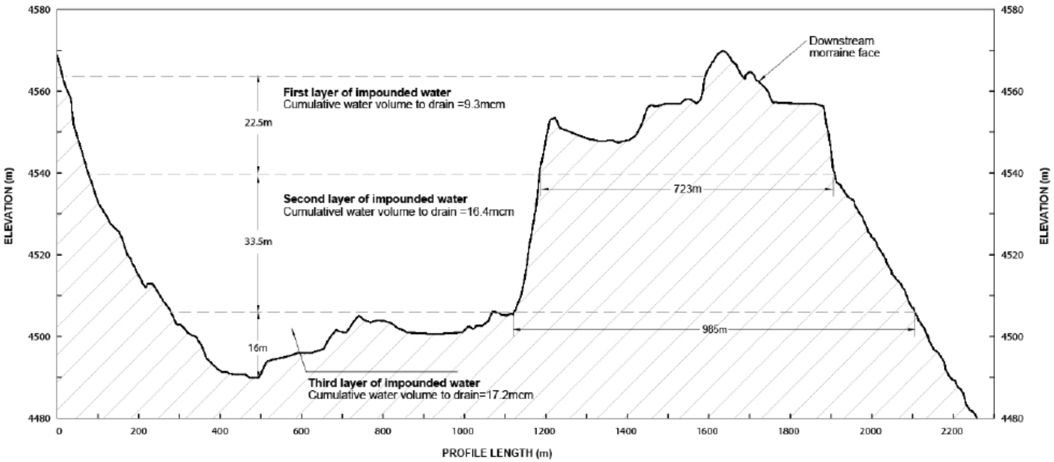

Figure 3. Palcacocha Lake and moraine partial longitudinal profile.

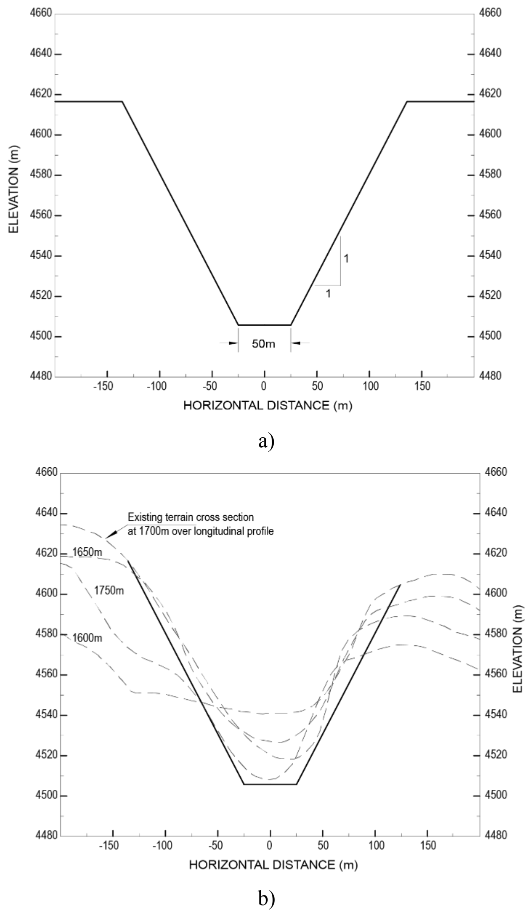

Figure 4. Maximum potential breach definition: **(a)** breach shape; **(b)** overlapping between the potential breach and existing terrain cross-sections across the last 200 m of eroded moraine.

NHESSD
2, 5971–6002, 2014

Predicting outflow induced by moraine failure in glacial lakes

D. S. Rivas et al.

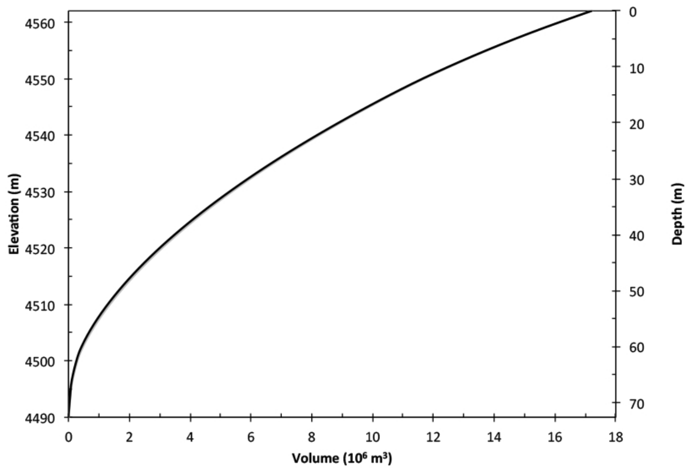

Figure 5. Volume/Elevation/Depth curves for Lake Palcacocha.

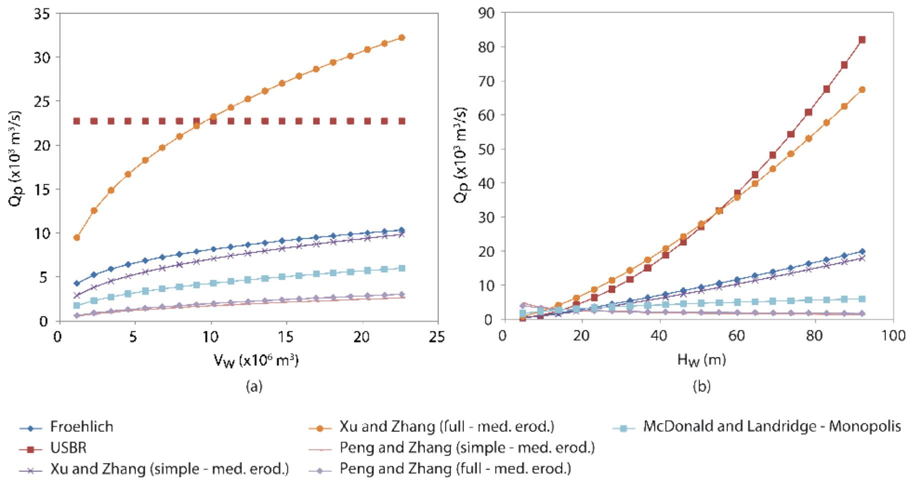

Figure 6. Peak flow response to **(a)** water volume variations, and **(b)** water depth variations according to selected empirical models.

NHESSD
2, 5971–6002, 2014

Predicting outflow induced by moraine failure in glacial lakes

D. S. Rivas et al.

NHESSD

2, 5971–6002, 2014

Predicting outflow induced by moraine failure in glacial lakes

D. S. Rivas et al.

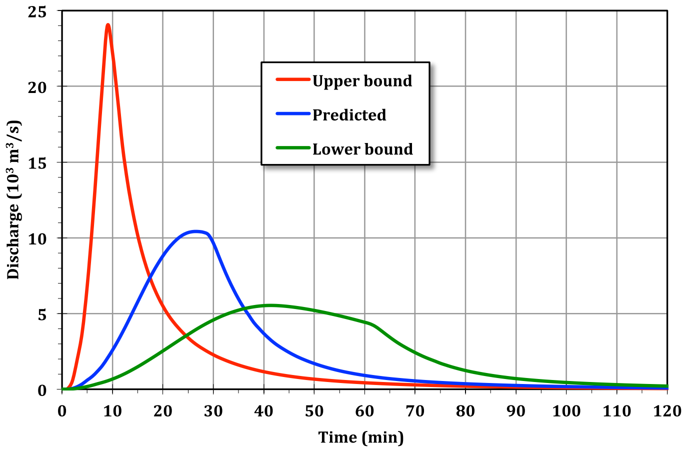

Figure 7. Potential outflow hydrographs from Lake Palcacocha due to a 56 m moraine breach.