Referee #2 – Adam Emmer

Dear Dr. Emmer:

We appreciate your interest in our article, and we think that the revised version of this manuscript reflects the influence of your comments and addresses your main concerns.

The reviewed article pays increased attention to supporting the selection of Lake Palcacocha as the case study and overall to support the worst breach scenario of failure. To do so, we have added information on historical cases of similar massive moraine failures and their characteristics, identifying the lack of bedrock as one of the determinant factors preventing total collapse of moraine dams, and providing additional data on the limited geomorphological and geotechnical characteristics of the moraine. That information provides more solid support for the worst breach hypothesis. We also analyzed the differences between the pre- and post-1941 moraine geometry at Palcacocha to explain how the moraine failed in 1941 and its likelihood to fail now.

Likewise we recognize the need of a two-phase GLOF to produce the collapse of the moraine, indicating similar cases where that kind of phenomena has occurred.

Further and deeper explanations of the changes to the article appear below, according to your specific comments, pointing out the location of each change in the revised manuscript.

Best regards

The Authors

Comment #1

The moraine dam of Lake Palcacocha failed in 1941; today's dam is characterized by a gentle slope of the downstream face of the dam (8°) in combination with huge dam body mass (width) and implementation of remedial works reinforcing the outlet against erosion and increasing dam freeboard. I find the failure of today's dam of Lake Palcacocha as a highly unlike scenario, unlike the dam overtopping (see also Emmer and Vilímek, 2014)

Response # 1

Since 1941, Lake Palcacocha evolved in such a way that a new setting of the lake and moraine emerged behind the remains of the old moraine. Palcaraju glacier has continued retreating, allowing the lake to deepen and grow upglacier, so that the bottom of the breach left by the 1941 glacial lake outburst flood (GLOF) is now the front of the current moraine (Figure 3). As a result, the dimensions and shape of both the lake and moraine have changed; as Lake Palcacocha's volume has grown ($14x10^6$ m^3 in 1941 to at least 17.2 $x10^6$ m^3 in 2009), the width-to-height ratio (DWH) of the moraine also increased from 6.3 to 14.9. [Please see these clarifications below and in the revised manuscript P7L9-26]

"Since 1941, Lake Palcacocha evolved in such a way that a new setting of the lake and moraine emerged behind the remains of the old moraine. During the catastrophic 1941 flood, the breach downcutting stopped as the lake was getting empty and the water level approached the lake bottom. That lake bottom and, indeed, the whole coupled system of moraine and lake were different to what exists now. Fig. 3 reveals a profile running along Lake Palcacocha and its current moraine (derived from a 5 m DEM by the Ministry of Environment of Peru) (Horizons, 2013), and a reconstruction of the moraine profile before 1941 (projected from non-breached adjacent portions of the end moraine). Palcaraju Glacier has continued retreating; allowing the lake to deepen and grow upglacier, so that the bottom of the breach left by the 1941 GLOF is now the front of the current moraine (Fig. 3). Satellite images from ASTER mission (Fig. 4) illustrate the acceleration of those retreat-induced changes over the last decade, showing the predominant retreat direction of Palcaraju Glacier and the growth trend of Lake Palcacocha. For instance, by 2012 the lake had approximately doubled the length it exhibited in 2000, moving its deepest point towards northeast. The deepest point of the lake in the 2009 survey (≈ 70 m) was not even within the domain of Lake Palcacocha in 1941. As a result, the dimensions and shape of both the lake and moraine have changed; as the volume of Lake Palcacocha has increased ($14x10^6$ m^3 in 1941 to $17.2x10^6$ m^3 in 2009), the DWH of the moraine also increased from 6.3 to 14.9."

Regardless of the apparent morphological stability provided by the DWH ratios, the breach of the Lake Palcacocha moraine virtually drained all of the impounded lake water behind it in 1941 (leaving something like $0.5x10^6$ m^3), creating a breach that is still in place (Figure 2). The massive failure of this moraine in 1941 might indicate that the moraine morphology—apparently stable—is not driving its likelihood to fail. In contrast, hydraulic and geotechnical parameters do seem to dominate the stability conditions of the whole moraine. High DWH ratios are recurrent in glacial lake moraine dams in the Cordillera Blanca. Qualitative, semi-quantitative, and quantitative assessments of the potential for outbursts in this area estimate that, despite their high DWH ratios, Lakes Quitacocha, Checquiacocha, Palcacocha, and Llaca are susceptible to outburst (Emmer and Vilímek, 2013) because of susceptibility factors like proximity between lake and glacier tongue, icefall or landslide likelihood, or short moraine freeboards. These assessments consistently identify Lake Palcacocha as one of the glacier lakes most prone to a GLOF in the region, as long as a trigger event (e.g., an avalanche in the form of an icefall) creates an overtopping wave, favoring continuous further erosion of the front end of the moraine. Without this overtopping wave, current drainage structures prevent the water level from exceeding the current 8 m freeboard, preventing any flow over the moraine dam. [Please see these clarifications below and in the revised manuscript P11L24-P12L11]

"Regardless the apparent morphological stability provided by its DWH ratios, the Palcacocha moraine virtually drained all of the impounded lake water behind it in 1941 (leaving something like $0.5x10^6$ m^3,), creating a breach that is still in place (Figure 2). The massive failure of this moraine in 1941 might indicate that the moraine morphology—apparently stable—is not driving its likelihood to fail. In contrast, hydraulic, freeboard, and geotechnical parameters do seem to dominate the stability conditions of the whole moraine. High DWH ratios are recurrent in moraine dams in the Cordillera Blanca. Qualitative, semi-quantitative, and quantitative assessments on potential for outbursts in this area estimate that, despite their high DWH ratios, Lakes Quitacocha, Checquiacocha, Palcacocha, and

Llaca are susceptible to outbursts (Emmer and Vilímek, 2013) because of susceptibility factors like proximity between lake and glacier tongue, icefall or landslide likelihood, or short moraine freeboards. These assessments consistently identify Lake Palcacocha as one of the glacial lake settings most prone to GLOFs in the region, as long as a trigger event (e.g., an avalanche in the form of an icefall, rockfall, or rock avalanche) creates an overtopping wave, favoring continuous further erosion of the front end of the moraine. Without this overtopping wave, current drainage structures prevent the water level from exceeding the current 8 m freeboard, preventing any flow over the moraine dam. Although this study only addresses the second phase of a two-phase process of overtopping wave and moraine failure, it recognizes the dependency between both phenomena and does not suggest that, in terms of hazard, one phenomenon dominates over the other."

Comment #2

In the case of Lake Palcacocha, significant specifics such as dam geometry influenced by the previous dam failure and the implemented remedial works must be considered when thinking about potential for dam failure in the future; nevertheless, none of presented methods for the estimation of peak flow and failure time (Table 1) reflect this condition (I dare to say, that these methods are not designed for potential failure of already failed and in addition also remediated dam), therefore I found these results based on unrealistic assumptions; to realize the improbability of a Lake Palcacocha dam failure it is illustrative to realize, that even during the catastrophic 1941 flood, the breach stopped at the current level, for further (deeper) breaching, the peak discharge, therefore, would have to be greater than it was in 1941.

Response # 2

During the catastrophic 1941 flood from Lake Palcacocha, the breach did stop at the current level. However, in 1941 the lake bottom and, indeed, the whole coupled system of moraine and lake were different. The lake bottom in 1941 was above the current bottom of the lake. Since 1941 the lake grew vertically and longitudinally (upglacier) due to glacier retreat (Figure 3). Today's deepest point of the lake (≈ 70 m) was not even within the domain of Lake Palcacocha in 1941.

We have added a deeper analysis of pre- and post-1941 moraine morphology in this revised version of the manuscript. Figure 3 suggests that, as a result of glacier retreat, the dimensions and shape of both the lake and moraine changed after 1941; as Lake Palcacocha's volume grew ($14x10^6$ m^3 in 1941 to 17.2 $x10^6$ m^3 in 2009), the width-to-height ratio (DWH) of the moraine also increased from 6.3 to 14.9. The need of an overtopping wave to induce further erosion failure recognizes that current drainage structures and remedial works prevent flow over the dam unless a trigger event generates such a wave. Hence, erosion independent events are unlikely to completely collapse the moraine dam of Lake Palcacocha. However, at Lake Palcacocha, there is no evidence to suggest that a flood produced only by overtopping waves might create higher hazards than the further erosion-collapse of the moraine. Although we are only approaching the second phase of the two-phase process of overtopping wave and moraine failure, we are not suggesting that, in terms of hazard, one process dominates over the other.

[Please see these clarifications below and in the revised manuscript P7L9-26, including the analysis of Figure 4, which shows the growth trend of Lake Palcacocha over the last two decades].

"Since 1941, Lake Palcacocha evolved in such a way that a new setting of the lake and moraine emerged behind the remains of the old moraine. During the catastrophic 1941 flood, the breach downcutting stopped as the lake was getting empty and the water level approached the lake bottom. That lake bottom and, indeed, the whole coupled system of moraine and lake were different to what exists now. Fig. 3 reveals a profile running along Lake Palcacocha and its current moraine (derived from a 5 m DEM by the Ministry of Environment of Peru) (Horizons, 2013), and a reconstruction of the moraine profile before 1941 (projected from non-breached adjacent portions of the end moraine). Palcaraju Glacier has continued retreating; allowing the lake to deepen and grow upglacier, so that the bottom of the breach left by the 1941 GLOF is now the front of the current moraine (Fig. 3). Satellite images from ASTER mission (Fig. 4) illustrate the acceleration of those retreat-induced changes over the last decade, showing the predominant retreat direction of Palcaraju Glacier and the growth trend of Lake Palcacocha. For instance, by 2012 the lake had approximately doubled the length it exhibited in 2000, moving its deepest point towards northeast. The deepest point of the lake in the 2009 survey (≈ 70 m) was not even within the domain of Lake Palcacocha in 1941. As a result, the dimensions and shape of both the lake and moraine have changed; as the volume of Lake Palcacocha has increased ($14x10^6$ m^3 in 1941 to $17.2x10^6$ m^3 in 2009), the DWH of the moraine also increased from 6.3 to 14.9."

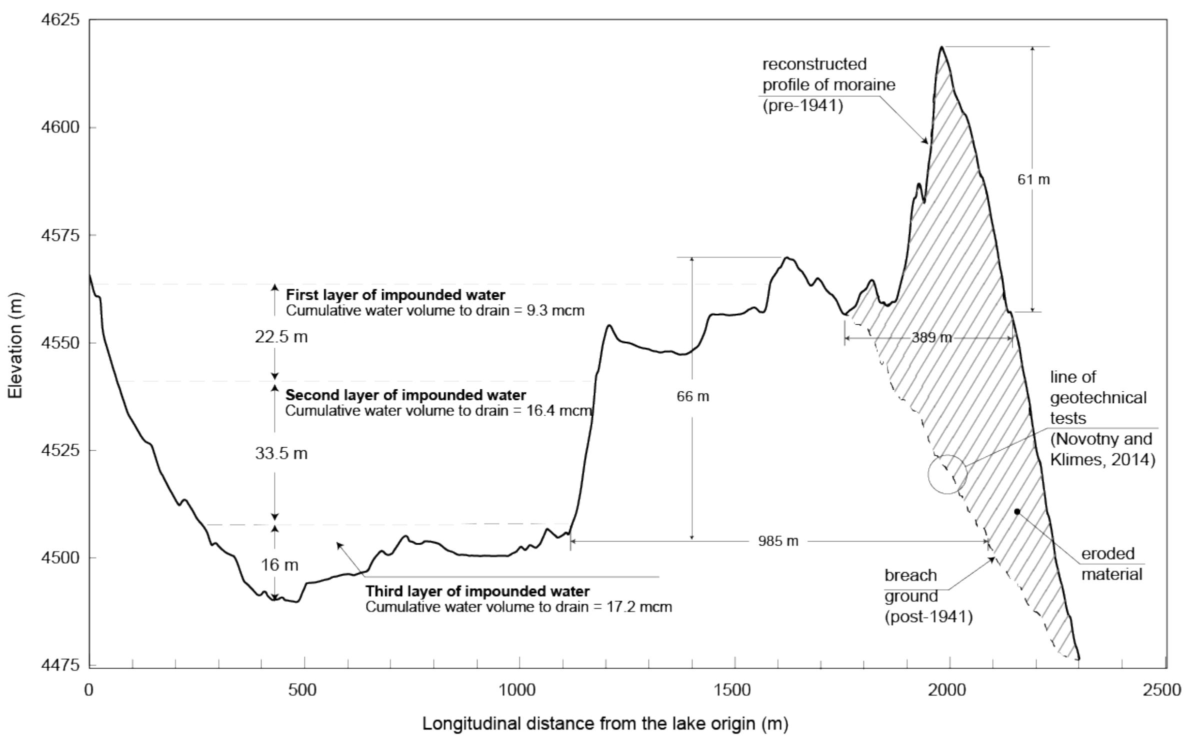

Figure 3. Palcacocha Lake and moraine longitudinal profile revealing differences between the post-1941 current moraine and a reconstruction of the moraine profile before 1941 (projected from non-breached adjacent portions of the end moraine)

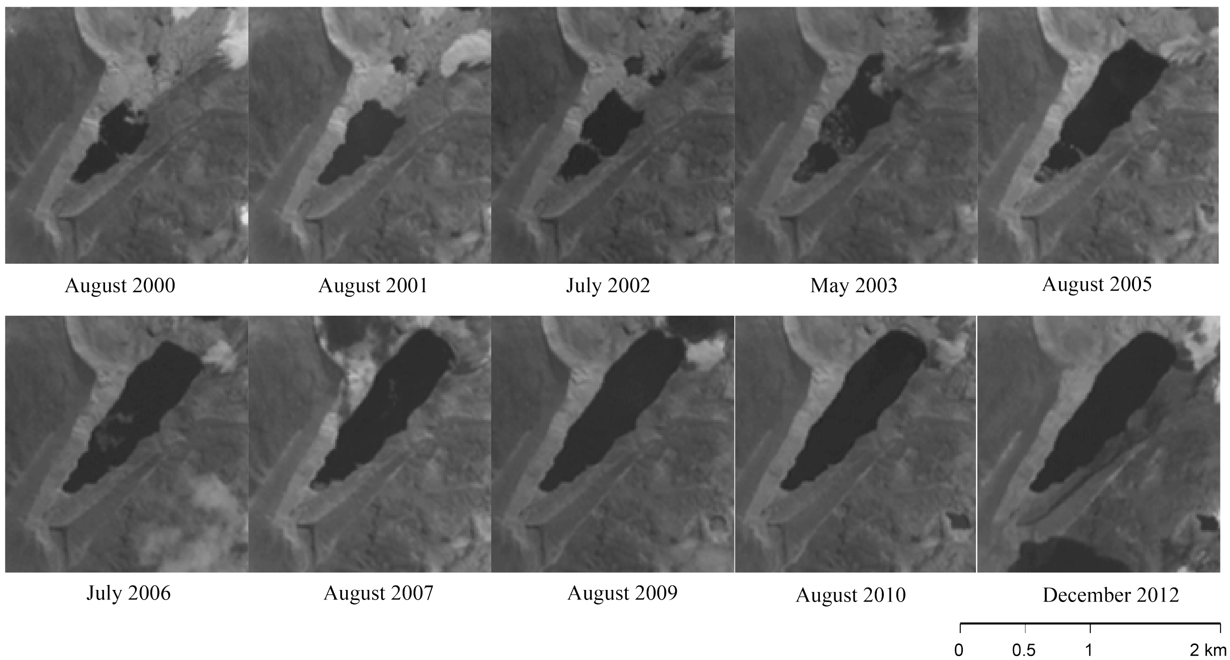

Figure 4. Growth pattern of Lake Palcacocha from 2000-2012: a sequence of ASTER satellite images reveal that the lake growth is following the glacier-retreat direction, changing the morphology of the lake's bottom (ASTER data from NASA Land Processes Distributed Active Archive Center).

Comment #3

Notwithstanding, if we think about potential dam failure of today's dam of Lake Palcacocha, it emerges, that dam failure (breach) could be only initiated by extreme high volume fast slope movement (icefall, rockfall, rock avalanche, …) into the lake, producing a displacement wave large enough to initiate erosion of the dam, despite its rather flat geometry and implemented remedial works; it was shown by Kershaw et al. (2005) at Queen Bess lake case study, that such a scenario leads to the two phases of an outburst flood, of which the first phase following dam overtopping was characterized by higher peak discharge than the second phase (dam failure); dam overtopping is, therefore, in any case, more actual and also a likely GLOF scenario for Lake Palcacocha and I suggest to concentrate on dam overtopping rather than on speculative dam failure, which would have to be preceded by dam overtopping with probable higher discharge than dam failure itself.

Response # 3

Although our research group at the Center for Research in Water Resources at UT Austin is also working on simulating overtopping waves in Lake Palcacocha and assessing multiple scenarios for that case, this paper aims to address solely the erosion collapse of the moraine. This work is part of a series of efforts to simulate a chain of GLOF processes including phenomena like avalanche, overtopping waves, erosion-collapse, and flooding in Huaraz City. We understand that the reviewer is concerned about the likelihood and size of a breach; however, that is not the scope of the paper. The focus of the paper is mainly on the approach, how to calculate discharge hydrographs when you have no other data or model to calculate that.

Additionally, the breach scale we are addressing, requiring erosion and movement of large moraine masses, is not uncommon in the history of GLOFs. In 1997 an ice avalanche over Queen Bess Lake (Canada) produced overtopping waves that started a breaching process of the moraine dam. The resulting breach reached lengths over 600 m and depths between 15-25 m, releasing $8x10^6$ m^3 of impounded water; Nostetuko Lake (Canada) suffered the same kind of two-phase GLOF in 1983, which created a massive breach failure (480 m-length and 40 m-depth) (Clague and Evans, 2000). In South America, Lake Cerro Largo (Patagonian Andes) attracts attention because a GLOF in 1989 drained $24.73x10^6$ m^3 out of the lake, carving a 500 m length breach; a more recent GLOF in the Patagonian Andes region discharged $10x10^6$ m^3 (4100 m^3/s) from Lake Ventisquero Negro in 2009, eroding a 350 m long breach with depths up to 50 m (Clague and Evans, 2000; Worni et al, 2012). The 1941 Palcacocha GLOF itself formed a breach through the moraine dam with a total length over 500 m (Figure 3). Queen Bess Lake and Lake Cerro Largo, despite their large magnitude breaches, represent rare cases of partial moraine failure, where a relevant factor preventing deeper breaches and total collapse was the presence of bedrock within the moraine dams, making further downcutting practically impossible (Clague and Evans, 2000). [Please see these clarifications below and in the revised manuscript P10L8-P11L2]

"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 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. This breach scale, requiring erosion and movement of large moraine masses, is not uncommon in the history of GLOFs. In 1997 an ice avalanche over Queen Bess Lake (Canada) produced overtopping waves that started a breaching process of the moraine dam. The resulting breach reached lengths over 600 m and depths between 15-25 m, releasing $8x10^6$ m^3 of impounded water; Nostetuko Lake (Canada) suffered the same kind of two-phase GLOF in 1983, which created a massive breach failure (480 m-length and 40 m-depth) (Clague and Evans, 2000). In South America, Lake Cerro Largo (Patagonian Andes) attracts attention because a GLOF in 1989 drained $24.73x10^6$ m^3 out of the lake, carving a 500 m length breach; a more recent GLOF in the Patagonian Andes region discharged $10x10^6$ m^3 (4100 m^3/s) from Lake Ventisquero Negro in 2009, eroding a 350 m length breach with depths up to 50 m (Clague and Evans, 2000; Worni et al, 2012). In 1998 a GLOF eroded the moraine dam of Tam Pokhari Lake (Mt. Everest region of Nepal), releasing a water volume of $18x10^6$ m^3; the resulting breach length exceeded 500 m, with an average width and height of 60 m and 50 m (Osti and Egashira, 2009). The 1941 Palcacocha GLOF itself formed a breach through its moraine dam with a total length over 500 m (Figure 3). Queen Bess Lake and Lake Cerro Largo, despite their large magnitude breaches, represent rare cases of *partial moraine failure*, where a relevant factor preventing deepest breaches and total collapse was the presence of bedrock within the moraine dams, making further downcutting practically impossible (Clague and Evans, 2000)."

We recognize the need of an overtopping wave to induce further erosion failure; we also recognize that current drainage structures and remedial works prevent flow over the dam unless a trigger event generates such a wave. Hence, erosion independent events are unlikely to completely collapse the moraine dam of Lake Palcacocha. However, at Lake Palcacocha, there is no evidence to suggest that a flood produced only by overtopping waves might create higher hazards than the further erosion-collapse of the moraine. Although we are only approaching the second phase of the two-phase process of overtopping wave and moraine failure, we are not suggesting that, in terms of hazard, one process dominates over the other. [Please see these clarifications below and in the revised manuscript P11L24-P12L11]

"Regardless the apparent morphological stability provided by its DWH ratios, the Palcacocha moraine virtually drained all of the impounded lake water behind it in 1941 (leaving something like $0.5x10^6$ m^3,), creating a breach that is still in place (Figure 2). The massive failure of this moraine in 1941 might indicate that the moraine morphology—apparently stable—is not driving its likelihood to fail. In contrast, hydraulic, freeboard, and geotechnical parameters do seem to dominate the stability conditions of the whole moraine. High DWH ratios are recurrent in moraine dams in the Cordillera Blanca. Qualitative, semi-quantitative, and quantitative assessments on potential for outbursts in this area estimate that, despite their high DWH ratios, Lakes Quitacocha, Checquiacocha, Palcacocha, and Llaca are susceptible to outbursts (Emmer and Vilímek, 2013) because of susceptibility factors like proximity between lake and glacier tongue, icefall or landslide likelihood, or short moraine freeboards. These assessments consistently identify Lake Palcacocha as one of the glacial lake settings most prone to GLOFs in the region, as long as a trigger event (e.g., an avalanche in the form of an icefall, rockfall, or rock avalanche) creates an overtopping wave, favoring continuous further erosion of the front end of the moraine. Without this overtopping wave, current drainage structures prevent the water level from exceeding the current 8 m freeboard, preventing any flow over the moraine dam. Although this study only addresses the second phase of a two-phase process of overtopping wave and moraine failure, it recognizes the dependency between both phenomena and does not suggest that, in terms of hazard, one phenomenon dominates over the other."

Additionally, if a model already exists that includes scouring and it is reliable, then it is better to include it since it proves that in a given event the moraine can be breached if the cohesion is low, and it can be used as a "calibration" for the simple methodology that is presented in this paper.

Referee #2 – Adam Emmer's Specific Comments

Comment P5972L2 - "glacial lake outburst floods" (see also Richardson and Reynolds, 2000)

Response P5972L2 - Suggestion accepted, the term "glacial lake outburst floods" is used in the whole revised manuscript

Comment P5972L22 - "flood risk" depends on several factors, not only capacity of the reservoir

Response P5972L22 - We rephrased that sentence, replacing "capacity" for "capability"

Comment P5972L22 - I'm not sure about the term "natural earthen dam"

Response P5972L22 - We agree, see the term "natural dam" is used in the revised version of the manuscript.

Comment P5980L16 - I suggest not to include "Study area" section as a part of the Methodology section

Response P5980L16 - We accept the suggestion, rearranging the manuscript structure:

1. Introduction
2. Study area
3. Methodology
   3.1 Overview
   3.2 Worst breach scenario: a link in a chain of GLOF processes
   3.3 Peak Flow and Failure Time Estimation
   3.4 Dam Breach Hydraulic Simulation
   3.5 Assessment of Empirical Equation Performance
   3.6 Model Selection and Probabilistic Assessment
4. Results and Discussion
   4.1 Comparison of empirical models
   4.2 Comparison of Empirical and DAMBRK Model Results
   4.3 Limitations and advantages
5. Conclusion

Comment P5981L20

"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." – How do you know, that there is absence of bedrock ?? please, provide references

Response P5981L20

There are few geological or geotechnical studies of the current composition of the Lake Palcacocha 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 (Novotny and Klimes, 2014). The moraine front surface at Lake Palcacocha currently exhibits what was the 1941 breach bottom. The differences between soil matrices at the rear and front zones of that breach channel, as well as at the crest of the moraine prior to 1941, reveal the heterogeneous and stratified structures composing Lake Palcacocha's moraine. Lower elevation soil samples (shallow samples at depths of 0.1 m below the breach surface) are generally coarser (well-graded gravel, silty gravel, or clayey gravel) than those of higher layers of the same moraine, where clayey sand or silty sand soils predominate (Novotny and Klimes, 2014). [Please see these clarifications below and in the revised manuscript P6L28-P7L8]

"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 or geotechnical 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 (Novotny and Klimes, 2014). The front surface of the moraine at Lake Palcacocha currently exhibits what was the bottom of the 1941 breach. The differences between soil matrices at the rear and front zones of that breach channel, as well as at the crest of the moraine prior to 1941, reveal the heterogeneous and stratified structures comprising Palcacocha's moraine. Lower elevation soil samples (shallow samples at depths of 0.1 m below the breach surface) are generally coarser (well-graded gravel, silty gravel, or clayey gravel) than those of higher layers of the same moraine, where clayey sand or silty sand soils predominate (Novotny and Klimes, 2014)."

The inner structure of the soil matrix beyond the 1941 breach bottom is unknown. Novotny and Klimes (2014) estimate that Lake Palcacocha's moraine bedrock might include granitic/sedimentary structures, though the depth at which those bedrock structures lie is not measured. If the sampled soil stratification is constant through the moraine, no bedrock should exist above the lake bottom elevation. [Please see these clarifications below and in the revised manuscript P11L3-8]

"The inner structure of the soil matrix beyond the 1941 breach bottom of Lake Palcacocha's moraine is unknown. Novotny and Klimes (2014) estimate that Lake Palcacocha's moraine bedrock might include granitic/sedimentary structures, though the depth at which those bedrock structures lie is not measured. If sampled soils stratification is constant through the moraine, no bedrock should exist above the lake bottom, reinforcing the no bedrock hypothesis and worst breach scenario adopted in this study."

Comment P5982L2

"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." - May I recommend to focus on realistic scenario for the given lake (dam overtopping in case of Lake Palcacocha), or to focus on lakes, for which dam failure is realistic scenario

Response P5982L2

The breach scale we are addressing, requiring erosion and movement of large moraine masses, is not uncommon in the history of GLOFs. In 1997 an ice avalanche over Queen Bess Lake (Canada) produced overtopping waves that started a breaching process of the moraine dam. The resulting breach reached lengths over 600 m and depths between 15-25 m, releasing $8x10^6$ m^3 of impounded water; Nostetuko Lake (Canada) suffered the same kind of two-phase GLOF in 1983, which created a massive breach failure (480 m-length and 40 m-depth) (Clague and Evans, 2000). In South America, Lake Cerro Largo (Patagonian Andes) attracts attention because a GLOF in 1989 drained $24.73x10^6$ m^3 out of the lake, carving a 500 m length breach; a more recent GLOF in the Patagonian Andes region discharged $10x10^6$ m^3 (4100 m^3/s) from Lake Ventisquero Negro in 2009, eroding a 350 m length breach with depths up to 50 m (Clague and Evans, 2000; Worni et al, 2012). The 1941 Palcacocha GLOF itself formed a breach through the moraine dam with total lengths over 500 m (Figure 3). Queen Bess Lake and Lake Cerro Largo, despite their large magnitude breaches, represent special cases of partial moraine failure, where presence of bedrock within the moraine dams prevented their total collapse, making further downcutting practically impossible (Clague and Evans, 2000). [Please see response to Comment #3 above]

The inner structure of the soil matrix beyond the 1941 breach bottom is unknown. Novotny and Klimes (2014) estimate that Lake Palcacocha's moraine bedrock might include granitic/sedimentary structures, though the depth at which those bedrock structures lie is not measured. If the sampled soil stratification is constant through the moraine, no bedrock should exist above the lake bottom elevation. [Please see response to Comment P5981L20 above]

Comment P5987L8 - The list of references seems incomplete to me – I miss key papers focusing on the broader environmental as well as social context of phenomenon of outburst floods in the Cordillera Blanca (e.g., Lliboutry et al., 1977; Zapata, 2002; Reynolds, 2003; Carey, 2005; Carey et al., 2012) and also some papers focusing on the GLOFs hazard estimation (e.g., McKillop and Clague, 2007a,b; Wang et al., 2012; Emmer and Vilímek, 2013, 2014), or general aspects of GLOFs (Clague and Evans, 2000; Richardson and Reynolds, 2000)

Response P5987L8 - We have extended the list of references to include:

Carey, M.: Living and dying with glaciers: people's historical vulnerability to avalanches and outburst floods in Peru. Global and Planetary Change, 47(2-4), 122–134. doi:10.1016/j.gloplacha.2004.10.007, 2005.

Clague, J. J., & Evans, S. G. A review of catastrophic drainage of moraine-dammed lakes in British Columbia. Quaternary Science Reviews, 19, 1763–1783, 2000.

Emmer A, Cochachin A.: Causes and mechanisms of moraine dammed lake failures in Cordillera Blanca (Peru), North American Cordillera and Central Asia. AUC Geographica 48(2), 5-15, 2013.

Emmer, A. and Vilímek, V.: Review Article: Lake and breach hazard assessment for moraine-dammed lakes: an example from the Cordillera Blanca (Peru), Nat. Hazards Earth Syst. Sci., 13, 1551–1565, doi:10.5194/nhess-13-1551-2013, 2013.

Hubbard, B., Heald, A., Reynolds, J. M., Quincey, D., Richardson, S. D., Luyo, M. Z., Portilla, N. S. and Hambrey, M. J. Impact of a rock avalanche on a moraine-dammed proglacial lake: Laguna Safuna Alta, Cordillera Blanca, Peru. Earth Surf. Process. Landforms, 30: 1251–1264, 2005.

Kershaw, J.A., Clague, J.J., and Evans, S.G.: Geomorphic and sedimentological signature of a two phase outburst flood from moraine-dammed Queen Bess Lake, British Columbia, Canada, Earth Surface Processes and Landforms, 30, 1-25, 2005.

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.

Wang, X., Liu, S., Ding, Y., Guo, W., Jiang, Z., Lin, J., & Han, Y. (2012). An approach for estimating the breach probabilities of moraine-dammed lakes in the Chinese Himalayas using remote-sensing data. Natural Hazards and Earth System Science, 12(10), 3109–3122. doi:10.5194/nhess-12-3109-2012.

Worni, R., Stoffel, M., Huggel, C., Volz, C., Casteller, A., & Luckman, B. Analysis and dynamic modeling of a moraine failure and glacier lake outburst flood at Ventisquero Negro, Patagonian Andes (Argentina). Journal of Hydrology, 444-445, 134–145. doi:10.1016/j.jhydrol.2012.04.013, 2012.

Anonymous Referee #1 - Concluding comments

Dear Reviewer:

We appreciate your comments and your attention to the relevance of moraine failure prediction and the safety of glacial lakes. This revised version of the article aims to address and clarify the major concerns you are paying attention to.

From the introduction we are trying to draw the readers' attention to the uncertainty aspects of dam breach prediction. We understand that underestimating future dam failures might lead to ineffective mitigation actions, exposing people to severe danger. On the other hand, we also recognize that overestimating their magnitude might lead to creating an atmosphere of concern in communities that, otherwise, also depend on water resources coming from glaciers. In this context, *uncertainty* aspects surround moraine failure estimation because of the physical nature of moraines and because of the range of dangers they create. Accounting for this uncertainty in predictive models should help inform broader flood risk analyses and lead to better mitigation actions, which we are trying to do.

The reviewed article also adds information on historical cases of similar massive moraine failures and their characteristics, providing additional data on the limited geomorphological and geotechnical characteristics of the moraine. That information provides a more solid support to the worst breach hypothesis we are presenting.

The approach and the models we are using (DAMBRK and empirical equations) preserves the objective of our predictive approach: we seek to provide a simple approach to quantify potential outflow (hydrographs) from breach failures, asses the results, and calculate their uncertainty. We are stating the limitations of these models and explaining how DAMBRK is serving to screen the results from the empirical equations, providing a comparison parameter in terms of the hydraulic capacity of a given breach section.

Further and deeper explanations of the changes along the article appears below, according to your comments, pointing out the location of each change in the revised manuscript.

Best regards

The Authors

Comment #1

Authors did not prove that the used breach model (DAMBRK) is suitable for the geotechnical/morphological setting of the studied moraine. On contrary, they characterize it as "over simplistic“(top of the page 5978) under the study conditions! They also do not explain, why the empirical models used may be adequate for the study site, e.g. if the models were defined on samples with similar geological and morphological conditions as the Palcacocha dam. Most importantly, they do not give any information convincing the reader, that the suggested worst case scenario is possible – they do not explain possible process, which may trigger such a massive breach; they do not show comparable cases from literature; they do not explain why overtopping wave with height of 100m in Safuna Alta (Hubbard et al. 2005) caused no breach despite its dam seems much less stable (much higher and much more narrow) compared with the Palcacocha lake dam; the only reason for the defined worst case scenario is lack of information and uncertainty. It is also not acceptable to present a worst case scenario which "likelihood is unclear", giving no further comments on probability of its occurrence.

Response # 1

Using the breach model (DAMBRK), the proposed approach seeks to determine whether empirical model estimations are hydraulically feasible for the study site. Coupled lake-breach settings cannot produce peak outflows out of the range of the hydraulic capacity of the breach or the available energy and volume of the lake. Under this approach, contrasting DAMBRK models and empirical models serves to measure the capability of empirical models to reproduce those coupled lake-breach settings. [Please see these clarifications below and in the revised manuscript P15L23-P16L3]

"Using the DAMBRK model, the proposed approach does not seek to thoroughly simulate hydro-erosive processes, but to determine whether empirical model estimations are hydraulically feasible for the study site. Coupled lake-breach settings cannot produce peak outflows out of the range of the hydraulic capacity of the breach or the available energy and volume of the lake. Under this approach, contrasting DAMBRK models and empirical models serves to reasonably measure the capability of empirical models to reproduce those coupled lake-breach settings. If the results of a given empirical model indicate that peak outflow estimations exceed the hydraulic capacity of the breach, such results are unrealistic or unfeasible. The capability of DAMBRK to simulate a breach conveyance capacity serves to screen and assess the empirical models performance and how suitable they are to represent the coupled lake-breach settings at the Palcacocha site. This assessment leads to hydrographs that can be considered robust and hydraulically consistent estimates of a potential dam breach."

Since 1941, Lake Palcacocha evolved in such a way that a new setting of the lake and moraine emerged behind the remains of the old moraine. Palcaraju glacier kept retreating, allowing the lake to deepen and grow upglacier, so that the bottom of the breach left by the 1941 GLOF is now the front of the current moraine (Figure 3). As a result, the dimensions and shape of both lake and moraine changed; as Lake Palcacocha's volume grew ($14x10^6$ m^3 in 1941 to 17.2 $x10^6$ m^3 in 2009), the width-to-height ratio (DWH) of the moraine also increased from 6.3 to 14.9. [Please see these clarifications below and in the revised manuscript P7L9-26]

"Since 1941, Lake Palcacocha evolved in such a way that a new setting of the lake and moraine emerged behind the remains of the old moraine. During the catastrophic 1941 flood, the breach downcutting stopped as the lake was getting empty and the water level approached the lake bottom. That lake bottom and, indeed, the whole coupled system of moraine and lake were different to what exists now. Fig. 3 reveals a profile running along Lake Palcacocha and its current moraine (derived from a 5 m DEM by the Ministry of Environment of Peru) (Horizons, 2013), and a reconstruction of the moraine profile before 1941 (projected from non-breached adjacent portions of the end moraine). Palcaraju Glacier has continued retreating, allowing the lake to deepen and grow upglacier, so that the bottom of the breach left by the 1941 GLOF is now the front of the current moraine (Fig. 3). Satellite images from ASTER mission (Fig. 4) illustrate the acceleration of those retreat-induced changes over the last decade, showing the predominant retreat direction of Palcaraju Glacier and the growth trend of Lake Palcacocha. For instance, by 2012 the lake had approximately doubled the length it exhibited in 2000, moving its deepest point towards northeast. The deepest point of the lake in the 2009 survey (≈ 70 m) was not even within the domain of Lake Palcacocha in 1941. As a result, the dimensions and shape of both the lake and moraine have changed; as the volume of Lake Palcacocha has increased ($14x10^6$ m^3 in 1941 to $17.2x10^6$ m^3 in 2009), the DWH of the moraine also increased from 6.3 to 14.9."

Regardless the apparent morphological stability provided by the DWH ratios, the Lake Palcacocha moraine virtually drained all of the impounded lake water behind it in 1941 (leaving something like $0.5x10^6$ m^3), creating a breach that is still in place (Figure 2). The massive failure of this moraine in 1941 might indicate that the moraine morphology—apparently stable—is not driving its likelihood to fail. In contrast, hydraulic and geotechnical parameters do seem to dominate the stability conditions of the whole moraine. High DWH ratios are recurrent in moraine dams in the Cordillera Blanca. Qualitative, semi-quantitative, and quantitative assessments on potential for outbursts in this area estimate that, despite their high DWH ratios, Lakes Quitacocha, Checquiacocha, Palcacocha, and Llaca are susceptible to outbursts (Emmer and Vilímek, 2013). These assessments consistently identify Lake Palcacocha as one of the glacial lake settings most prone to GLOFs in the region. [Please see these clarifications below and in the revised manuscript P11L24-P12L11]

"Regardless the apparent morphological stability provided by its DWH ratios, the Palcacocha moraine virtually drained all of the impounded lake water behind it in 1941 (leaving something like $0.5x10^6$ m^3,), creating a breach that is still in place (Figure 2). The massive failure of this moraine in 1941 might indicates that the moraine morphology—apparently stable—is not driving its likelihood to fail. In contrast, hydraulic, freeboard, and geotechnical parameters do seem to dominate the stability conditions of the whole moraine. High DWH ratios are recurrent in moraine dams in the Cordillera Blanca. Qualitative, semi-quantitative, and quantitative assessments on potential for outbursts in this area estimate that, despite their high DWH ratios, Lakes Quitacocha, Checquiacocha, Palcacocha, and Llaca are susceptible to outbursts (Emmer and Vilímek, 2013) because of susceptibility factors like proximity between lake and glacier tongue, icefall or landslide likelihood, or short moraine freeboards. These assessments consistently identify Lake Palcacocha as one of the glacial lake settings most prone to GLOFs in the region, as long as a trigger event (e.g., an avalanche in the form of an icefall, rockfall, or rock avalanche) creates an overtopping wave, favoring continuous further erosion of the front end of the moraine. Without this overtopping wave, current drainage structures prevent the water level from exceeding the current 8 m freeboard, preventing any flow over the moraine dam. Although this study only addresses the second phase of a two-phase process of overtopping wave and moraine failure, it recognizes the dependency between both phenomena and does not suggest that, in terms of hazard, one phenomenon dominates over the other."

In contrast, conditions around Safuna Alta are particularly different. The front moraine of Safuna Alta provides an 80 m tall freeboard (Hubbard et al., 2005). In that case, the full collapse of the moraine would require either that the initial (or reflected) waves completely destroy the moraine or that the waves create a deep enough breach to favor continuous overflow. Otherwise, overtopping erosion is not possible. In 2002, waves in Safuna Alta reached up to 100 m (Hubbard et al., 2005), overtopping the front moraine, but they were not able to create the 80 m breach required to allow continuous outflow from the lake. In contrast, the freeboard in Lake Palcacocha is an order of magnitude smaller (about 8 m), making the continuous outflow condition more likely. [Please see these clarifications below and in the revised manuscript P9L7-P10L7]

"This paper deals with only one of the processes of a potential GLOF chain at Lake Palcacocha: moraine breaching and lake emptying as a consequence of erosion. Therefore, we are envisioning a scenario where avalanches hitting the lake, and subsequent wave propagation, run-up, and overtopping already occurred, creating conditions to allow moraine breaching and continuous outflow from the lake.

As well as moraine material strength, freeboard (and all the sediment material behind it) plays a key role on allowing continuous outflow conditions to exist. If, after overtopping waves leave a moraine, the lake water level is not above the moraine crest, further drainage and hence erosion is not possible. Lake water level may exceed moraine elevation either because (i) an event within the chain of GLOF processes destroys or cracks freeboard-providing structures, (ii) a falling mass contributes to raising the volume and lake surface level, or (iii) a combination of both phenomena. For instance, in 2002 a rock avalanche produced a GLOF at Lake Safuna Alta (Cordillera Blanca), propagating a series of waves over 100 m in height, allowing them to overtop the impounding moraine; however, these waves were unable to initiate any massive erosion of the dam (Hubbard et al., 2005). At that time the freeboard at Lake Safuna Alta was about 80 m; although initial and seiche waves eroded the proximal and distal faces of the moraine, the resulting damage was insufficient to cause the lake level to exceed the moraine crest elevation after the wave overtopping (Hubbard et al., 2005).

Unlike Lake Safuna Alta, before 1941 Lake Palcacocha had no natural or artificial dams providing any stable freeboard. At that time the GLOF that killed over 5000 people downstream in Huaraz completed two stages of the GLOF chain: wave overtopping and moraine breaching (stage 4b in Fig. 5), practically emptying the lake. In 1970, a combination of natural, artificial dams, and drainage structures were built at Lake Palcacocha. These 8 m-tall and 40 m-wide structures, along with a drainage channel, were planned to provide stable freeboard to the lake, preventing water level from exceeding the moraine crest elevation (4570 m.a.s.l.) under the influence of extreme precipitation or glacier melting discharges (INDC, 2011). On the contrary, low height and width of these partially natural dams seems susceptible to large overtopping waves because of direct-impact destruction, instant mass discharge into the lake, or progressive erosion. For instance, spatial analysis over a 5 m DEM (Horizons, 2013) reveals that by receiving large icefalls Lake Palcacocha can instantly increase its volume, exceeding the additional impounding capacity provided by the current freeboard (a potential volume of 3.4×10^6 m^3 is contained between dam crest and regulated lake level)."

Comment #2

The presented result completely lacks any attempt at validation against objective data (or at least data/models independent from the author's pre-defined settings), though such data may be available considering the breach left by the 1941 event which description can be found in different sources (e.g. Carey 2010). Applying the approach to the historical event may indicate if it gives reasonable results or not and it could also provide some leads to the definition of the worst-case scenario. Authors "validate" output of two models with unknown reliability against each other, which is methodologically not acceptable.

Response # 2

The inner structure of the soil matrix beyond the 1941 breach bottom is unknown. Novotny and Klimes (2014) estimate that Palcacocha's moraine bedrock might include granitic/sedimentary structures, though the depth at which those bedrock structures lie is not measured. If sampled soils stratification is constant through the moraine, no bedrock should exist above the lake bottom, reinforcing the no bedrock hypothesis and worst case scenario adopted in this study. [Please see these clarifications below and in the revised manuscript P11L3-8]

"The inner structure of the soil matrix beyond the 1941 breach bottom of Lake Palcacocha's moraine is unknown. Novotny and Klimes (2014) estimate that Lake Palcacocha's moraine bedrock might include granitic/sedimentary structures, though the depth at which those bedrock structures lie is not measured. If sampled soils stratification is constant through the moraine, no bedrock should exist above the lake bottom, reinforcing the no bedrock hypothesis and worst breach scenario adopted in this study."

Note that the portion of the moraine that today could erode is well behind the 1941 erosion area, so that simulating the 1941 event may not be meaningful if our concern is current day hazard reduction. Also, quantitative information about the 1941 event do not exist that could be used to validate a current day model. Some morphological information may exist, but discharge, velocity and inundation data do not exist [Please see these clarifications in the revised manuscript on P15L3-13 and Figures 3 and 4 (shown above in Response to Comment #2 by Adam Emmer, showing differences between moraine geometry in 1941 and now, as well as the growth trend of Lake Palcacocha over the last decade).

"For most potentially dangerous glacial lakes, there is little (if any) data to calibrate hydraulic simulations, and essentially no independent data sets for validation. Note that the portion of the moraine at Lake Palcacocha that today could erode is well behind the 1941 GLOF erosion area (Figure 3), so that simulating the 1941 event for calibration purposes may not be meaningful if our concern is current day hazard reduction. Also, quantitative information about the 1941 event is not available that could be used to validate a current day model. We refer to data for validation as independent hydraulic data such as peak outflow, failure time, streamflow measurements, flood depths, or precise flooded areas. In the Cordillera Blanca, however, there is available only geomorphologic evidence of breach dimensions of historical GLOF events—breach dimensions remain over time, unless a new GLOF or severe geomorphic event reshape them (Hubbard et al., 2005; Novotny and Klimes, 2014)."

Anonymous Referee #1 - Supplement comments

Comment #1

The stated limitations suggest this model may be used for artificial dam breaches but it seems highly simplistic for moraine dam breaches, since the moraine is compound of highly heterogeneous material with size from clay to large rock blocks.

Response #1

We are assessing nine empirical models for estimating peak discharge and time of failure for both natural dams (heterogeneous material composition) and engineered dams. Changes were made to Table 1 in the revised manuscript to show the type of dams used for each model: engineered dams (Froehlich, 1995; USBR, 1982; Xu and Zhang, 2009; McDonald and Landridge – Monopolis, 1984), and natural dams (Peng and Zhang, 2012; Walder and O'Connor, 1997).

DAMBRK is a simplistic model from a morphologic or geotechnical point of view. However, under the proposed approach, the shape of the output hydrograph produced by DAMBRK will always meet two premises: both the peak flow and the time to peak flow match the results from an empirical screened model. Likewise, the volume under the hydrograph curve is physically constrained by the lake volume. This coupled assessment (empirical model/dam breach model) leads to outcomes that are statistically (regression analysis) and hydraulically possible.

Comment #2

By my knowledge, this is unrealistic assumption, which does not reflect real world processes of moraine dam breaches. Or do you know the authors about a case, where the moraine dam breach would start at its crest and develop as described here?

Response #2

This assumption does not reflect real world processes of moraine dam breaches. 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. The DAMBRK model, under the assumption of top-to-bottom breach development, intends to produce results equivalent to real dam breaches situations, not to thoroughly reproduce the process. The coupled modeling approach (empirical model/dam breach model) might provide constraining parameters (peak flow, time of failure, volume under the hydrograph) to assess and reach those equivalent results. [Please see these clarifications below and in the revised manuscript P14L16-24]

"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. This assumption does not reflect real world processes of moraine dam breaches. 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. The DAMBRK model, under the assumption of top-to-bottom breach development, intends to produce results equivalent to real dam breaches situations, not to thoroughly reproduce the process.

The coupled modeling approach (empirical model/dam breach model) might provide the constraining parameters (peak flow, time of failure, volume under the hydrograph) to reach those equivalent results."

Comment #3

This statement is not true even for the Cordillera Blanca - Lliboutry et al. 1977; Zapata 2002, some of the available literature also suggest geotechnical properties of the moraine material (Hubbard et al. 2005) and some describe even historical events from the Palcacocha Lake (Vilimek et al. 2005).

Response #3

For most potentially dangerous glacial lakes, there is little (if any) data to calibrate hydraulic simulations and essentially no independent data sets for validation. We refer to data for validation as *independent hydraulic data* such as peak outflow, failure time, streamflow measurements, flood depths, or precise flooded areas. In the Cordillera Blanca, however, there is available only geomorphologic evidence on breach dimensions of historical GLOF events—breach dimensions remain over time, unless a new GLOF or severe geomorphic event reshape them (Hubbard et al, 2005; Novotny and Klimes, 2014). [Please see these clarifications below and in the revised manuscript P15L3-13]

"For most potentially dangerous glacial lakes, there is little (if any) data to calibrate hydraulic simulations, and essentially no independent data sets for validation. Note that the portion of the moraine at Lake Palcacocha that today could erode is well behind the 1941 GLOF erosion area (Figure 3), so that simulating the 1941 event for calibration purposes may not be meaningful if our concern is current day hazard reduction. Also, quantitative information about the 1941 event is not available that could be used to validate a current day model. We refer to data for validation as independent hydraulic data such as peak outflow, failure time, streamflow measurements, flood depths, or precise flooded areas. In the Cordillera Blanca, however, there is available only geomorphologic evidence of breach dimensions of historical GLOF events—breach dimensions remain over time, unless a new GLOF or severe geomorphic event reshape them (Hubbard et al., 2005; Novotny and Klimes, 2014)."

Comment #4

Why do you compare results of the empirical models to the calibrated DAMBRK simulation, when you are not able to verify, which one is more precise and gives "better" results? DAMBRK model includes all uncertainties related to the empirical estimations and adds more related to the very simplistic assumptions about the modeled process. Therefore, I think that the DAMBRK model contains more uncertainties and is less reliable?

Response #4

Coupled lake-breach settings should not produce peak outflows out of the range of the hydraulic capacity of the breach or the available energy and volume of the lake. If the results of a given empirical model indicate that peak outflow estimations exceed the hydraulic capacity of the breach, such results are unrealistic or infeasible. The capability of DAMBRK to simulate a breach conveyance capacity serves to screen and assess the empirical models performance and how suitable they are to represent the coupled lake-breach settings at the Palcacocha site. This assessment leads to hydrographs that can be considered robust and hydraulically consistent estimates of a potential dam breach. [Please see these clarifications below and in the revised manuscript P15L23-P16L3]

"Using the DAMBRK model, the proposed approach does not seek to thoroughly simulate hydro-erosive processes, but to determine whether empirical model estimations are hydraulically feasible for the study site. Coupled lake-breach settings cannot produce peak outflows out of the range of the hydraulic capacity of the breach or the available energy and volume of the lake. Under this approach, contrasting DAMBRK models and empirical models serves to reasonably measure the capability of empirical models to reproduce those coupled lake-breach settings. If the results of a given empirical model indicate that peak outflow estimations exceed the hydraulic capacity of the breach, such results are unrealistic or unfeasible. The capability of DAMBRK to simulate a breach conveyance capacity serves to screen and assess the empirical models performance and how suitable they are to represent the coupled lake-breach settings at the Palcacocha site. This assessment leads to hydrographs that can be considered robust and hydraulically consistent estimates of a potential dam breach."

Comment #5

Every empirical model depends on site-specific characteristics, which may differ considerably from place to place. Do you think, that the chosen model was based on cases with similar characteristics as the Palcacocha Lake moraine?

Response #5

Under the proposed approach, selecting a proper empirical model does not rely on comparing individual characteristics of the lake or the moraine at the Palcacocha site. Instead, we propose that the behavior of a dam breach process depends on several factors, including hydraulic (lake) and geomorphology or geotechnical characteristics (moraine). Therefore, an integrated assessment of the breach process should not focus on isolated characteristics of the problem, but on evaluating the models output (outflow in this case). That evaluation consists of determining whether outflow results are reasonably realistic for the site conditions (is the predicted outflow conveyable through the breach given the lake volume, available potential energy, breach dimensions and failure time?) [Please see these clarifications below and in the revised manuscript P8L4-12]

"Under the proposed approach, selecting a proper empirical model does not rely on comparing individual characteristics of the lake or the moraine at the site. Instead, we propose that the behavior of a dam breach process depends on several factors, including hydraulic (lake) and geomorphology or geotechnical characteristics (moraine). Therefore, an integrated assessment of the breach process should not focus on isolated characteristics of the problem, but on evaluating the model output (outflow in this case). That evaluation consists of determining whether outflow results are reasonably realistic for the site conditions: is the predicted outflow conveyable through the breach given the lake volume, available potential energy, breach dimensions and failure time?"

The empirical models we have assessed address both natural and constructed dams (the types of dams were added to Table 1 in the revised manuscript). In comparison with landslide dams, moraines commonly possess steeper slopes (up to 40°) and smaller DWH (width to height) ratios (0.1 - 0.2), more comparable to those of constructed dams (Clague and Evans, 2000; Costa and Schuster, 1988). Huggel et al. (2004) estimates that DWH ratios less than one lead to high susceptibility of failure for moraine dams in the Swiss Alps, while moraines with DWH ratios higher than ten are not commonly expected to fail. Similar DWH ratios (0.6 < DWH < 1.7) represents high susceptibility thresholds for Himalayas recorded GLOF events (Wang et al, 2012). [Please see these clarifications below and in the revised manuscript P4L25-31]

"In comparison with landslide dams, moraine dams commonly possess steeper slopes (up to 40°) and smaller DWH ratios (0.1 - 0.2), more comparable to those of constructed dams (Clague and Evans, 2000; Costa and Schuster, 1988). Huggel et al. (2004) estimates that DWH ratios less than one lead to high susceptibility of failure for moraine dams in the Swiss Alps, while moraines with DWH ratios higher than ten are not commonly expected to fail. Similar DWH ratios (0.6 < DWH < 1.7) represent high susceptibility thresholds for Himalayan GLOF events (Wang et al., 2012)."

The width-to-height ratio (DWH) of Palcacocha's moraine changed from 6.3 (pre-1941) to 14.9 (post-1941). Regardless the apparent morphological stability provided by these DWH ratios, the Palcacocha moraine virtually drained all of the impounded lake behind it in 1941 (leaving something like 0.5×10^6 m^3), creating a breach that is still in place in front of the current lake. According to geomorphologic characteristics, the Palcacocha moraine was, and still is, unlikely to fail. However, the coupled evaluation we are proposing indicates otherwise. Qualitative, semi-quantitative, and quantitative assessments on potential for outbursts in Cordillera Blanca estimate that, despite their high DWH ratios, Lakes Quitacocha, Checquiacocha, Palcacocha, and Llaca are susceptible to outburst (Emmer and Vilímek, 2013). These assessments consistently identify Lake Palcacocha as one of the glacier lakes most prone to GLOF in the region. [Please see these clarifications below and in the revised manuscript P11L24-P12L11]

"Regardless the apparent morphological stability provided by its DWH ratios, the Palcacocha moraine virtually drained all of the impounded lake water behind it in 1941 (leaving something like 0.5×10^6 m^3,), creating a breach that is still in place (Figure 2). The massive failure of this moraine in 1941 might indicates that the moraine morphology—apparently stable—is not driving its likelihood to fail. In contrast, hydraulic, freeboard, and geotechnical parameters do seem to dominate the stability conditions of the whole moraine. High DWH ratios are recurrent in moraine dams in the Cordillera Blanca. Qualitative, semi-quantitative, and quantitative assessments on potential for outbursts in this area estimate that, despite their high DWH ratios, Lakes Quitacocha, Checquiacocha, Palcacocha, and Llaca are susceptible to outbursts (Emmer and Vilímek, 2013) because of susceptibility factors like proximity between lake and glacier tongue, icefall or landslide likelihood, or short moraine freeboards. These assessments consistently identify Lake Palcacocha as one of the glacial lake settings most prone to GLOFs in the region, as long as a trigger event (e.g., an avalanche in the form of an icefall, rockfall, or rock avalanche) creates an overtopping wave, favoring continuous further erosion of the front end of the moraine. Without this overtopping wave, current drainage structures prevent the water level from exceeding the current 8 m freeboard, preventing any flow over the moraine dam. Although this study only addresses the second phase of a two-phase process of overtopping wave and moraine failure, it recognizes the dependency between both phenomena and does not suggest that, in terms of hazard, one phenomenon dominates over the other."

Comment #6

[A Glacier Lake Outburst Flood (GLOF) occurred from Lake Palcacocha in 1941 – when the lake volume was about 12×106 m^3] Is it possible to find some more details about this event? E.g. affected area by the GLOF? Where did you get this information, please add reference.

Response #6

The specific information about the volume of the lake in available in the reference INDC (2011). Additional description of the 1941 event is provided in the revised manuscript. [Please see these clarifications below and in the revised manuscript P6L14-27]

"Lake Palcacocha and similar glacial lakes have emerged as a consequence of deglaciation processes occurring in the Cordillera Blanca region in Peru (Fig. 1 and Fig. 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 0.5×10^6 m^3 in 1947 to 17×10^6 m^3 in 2009, and a Glacial Lake Outburst Flood (GLOF) occurred from Lake Palcacocha in 1941—when the lake volume was about 12×10^6 m^3 (INDC, 2011). The 1941 GLOF caused extensive flooding in the downstream city of Huaraz, killing more than 5000 people (according to best estimates) and destroying infrastructure and agricultural land all the way to the coast (Carey, 2010; Evans et al., 2009). The recent increase in lake volume raises concerns of a persistent risk of flood for the downstream city of Huaraz. 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."

Reference:

INDC - 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.

Comment #7

I would suggest to move this paragraph as the first one (at least its first part) of this chapter.

Response #7

We accept the suggestion and moved the paragraph. Please also note general changes in the structure of the manuscript; we created an independent section to describe the study area:

1. Introduction
2. Study area
3. Methodology
   3.1 Overview
   3.2 Worst breach scenario: a link in a chain of GLOF processes
   3.3 Peak Flow and Failure Time Estimation
   3.4 Dam Breach Hydraulic Simulation
   3.5 Assessment of Empirical Equation Performance
   3.6 Model Selection and Probabilistic Assessment
4. Results and Discussion
   4.1 Comparison of empirical models
   4.2 Comparison of Empirical and DAMBRK Model Results
   4.3 Limitations and advantages
5. Conclusion

Comment #8

[There are few geological studies of the current composition of the moraine…] Could you list them?

Response #8

There are few geological or geotechnical 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 (Novotny and Klimes, 2014). The front surface of the moraine at Lake Palcacocha currently exhibits what was the 1941 breach bottom. The differences between soil matrices at the rear and front zones of that breach channel, as well as at the crest of the moraine prior to 1941, reveal the heterogeneous and stratified structures composing Palcacocha's moraine. Lower elevation soil samples (shallow samples at depths of 0.1 m below the breach surface) are generally coarser (well-graded gravel, silty gravel, or clayey gravel) than those of higher layers of the same moraine, where clayey sand or silty sand soils predominate (Novotny and Klimes, 2014). [Please see these clarifications below and in the revised manuscript P6L28-P7L8]

"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 or geotechnical 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 (Novotny and Klimes, 2014). The front surface of the moraine at Lake Palcacocha currently exhibits what was the bottom of the 1941 breach. The differences between soil matrices at the rear and front zones of that breach channel, as well as at the crest of the moraine prior to 1941, reveal the heterogeneous and stratified structures comprising Palcacocha's moraine. Lower elevation soil samples (shallow samples at depths of 0.1 m below the breach surface) are generally coarser (well-graded gravel, silty gravel, or clayey gravel) than those of higher layers of the same moraine, where clayey sand or silty sand soils predominate (Novotny and Klimes, 2014)."

Comment #9

[Second, in the case of Lake Palcacocha the worst-case breach depth is the full depth of the moraine] Is such a breach feasible? To what process, would you attributed a breach 55 m deep and 986 m long? Is something comparable in the literature?

Response #9

The breach scale we are addressing, requiring erosion and movement of large moraine masses, is not uncommon in the history of GLOF's. In 1997 an ice avalanche over Queen Bess Lake (Canada) produced overtopping waves that started a breaching process of the moraine dam. The resulting breach reached lengths over 600 m and depths between 15-25 m, releasing $8x10^6$ m^3 of impounded water; Nostetuko Lake (Canada) suffered the same kind of two-phase GLOF in 1983, which created a massive breach failure (480 m-length and 40 m-depth) (Clague and Evans, 2000). In South America, Lake Cerro Largo (Patagonian Andes) attracts attention because a GLOF in 1989 drained $24.73x10^6$ m^3 out of the lake, carving a 500 m length breach; a more recent GLOF in the Patagonian Andes region discharged $10x10^6$ m^3 (4100 m3/s) from Lake Ventisquero Negro in 2009, eroding a 350 m length breach with depths up to 50 m (Clague and Evans, 2000; Worni et al, 2012). The 1941 Palcacocha GLOF itself formed a breach through the moraine dam with total lengths over 500 m (Figure 3). Queen Bess Lake and Lake Cerro Largo, despite their large magnitude breaches, represent special cases of partial moraine failure, where presence of bedrock within the moraine dams prevented their total collapse, making further downcutting practically impossible (Clague and Evans, 2000). [Please see these clarifications below and in the revised manuscript P10L8-P11L2]

"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 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. This breach scale, requiring erosion and movement of large moraine masses, is not uncommon in the history of GLOFs. In 1997 an ice avalanche over Queen Bess Lake (Canada) produced overtopping waves that started a breaching process of the moraine dam. The resulting breach reached lengths over 600 m and depths between 15-25 m, releasing $8x10^6$ m^3 of impounded water; Nostetuko Lake (Canada) suffered the same kind of two-phase GLOF in 1983, which created a massive breach failure (480 m-length and 40 m-depth) (Clague and Evans, 2000). In South America, Lake Cerro Largo (Patagonian Andes) attracts attention because a GLOF in 1989 drained $24.73x10^6$ m^3 out of the lake, carving a 500 m length breach; a more recent GLOF in the Patagonian Andes region discharged $10x10^6$ m^3 (4100 m^3/s) from Lake Ventisquero Negro in 2009, eroding a 350 m length breach with depths up to 50 m (Clague and Evans, 2000; Worni et al, 2012). In 1998 a GLOF eroded the moraine dam of Tam Pokhari Lake (Mt. Everest region of Nepal), releasing a water volume of 18x10^6 m^3; the resulting breach length exceeded 500 m, with an average width and height of 60 m and 50 m (Osti and Egashira, 2009). The 1941 Palcacocha GLOF itself formed a breach through its moraine dam with a total length over 500 m (Figure 3). Queen Bess Lake and Lake Cerro Largo, despite their large magnitude breaches, represent rare cases of *partial moraine failure*, where a relevant factor preventing deepest breaches and total collapse was the presence of bedrock within the moraine dams, making further downcutting practically impossible (Clague and Evans, 2000)."

We recognize the need of an overtopping wave to induce erosion failure; we also recognize that current drainage structures and remedial works prevent flow over the dam unless a trigger event generates such a wave. Hence, erosion independent events are unlikely to completely collapse the moraine dam of Lake Palcacocha. [Please see these clarifications below and in the revised manuscript P11L24-P12L11]

"Regardless the apparent morphological stability provided by its DWH ratios, the Palcacocha moraine virtually drained all of the impounded lake water behind it in 1941 (leaving something like 0.5x10^6 m^3,), creating a breach that is still in place (Figure 2). The massive failure of this moraine in 1941 might indicates that the moraine morphology—apparently stable—is not driving its likelihood to fail. In contrast, hydraulic, freeboard, and geotechnical parameters do seem to dominate the stability conditions of the whole moraine. High DWH ratios are recurrent in moraine dams in the Cordillera Blanca. Qualitative, semi-quantitative, and quantitative assessments on potential for outbursts in this area estimate that, despite their high DWH ratios, Lakes Quitacocha, Checquiacocha, Palcacocha, and Llaca are susceptible to outbursts (Emmer and Vilímek, 2013) because of susceptibility factors like proximity between lake and glacier tongue, icefall or landslide likelihood, or short moraine freeboards. These assessments consistently identify Lake Palcacocha as one of the glacial lake settings most prone to GLOFs in the region, as long as a trigger event (e.g., an avalanche in the form of an icefall, rockfall, or rock avalanche) creates an overtopping wave, favoring continuous further erosion of the front end of the moraine. Without this overtopping wave, current drainage structures prevent the water level from exceeding the current 8 m freeboard, preventing any flow over the moraine dam. Although this study only addresses the second phase of a two-phase process of overtopping wave and moraine failure, it recognizes the dependency between both phenomena and does not suggest that, in terms of hazard, one phenomenon dominates over the other."

Comment #10

[Absence of bedrock and the prevailing presence of poor cohesion materials are likely in the Lake's moraine] Where does the information about bedrock come from? Why do you think there is no bedrock below the dam when the site in general lacks geological information?

Response #10

The inner structure of the soil matrix beyond the 1941 breach bottom is unknown. Novotny and Klimes (2014) estimate that Lake Palcacocha's moraine bedrock might include granitic/sedimentary structures, though the depth at which those bedrock structures lie is not measured. If sampled soils stratification is constant through the moraine, no bedrock should exist above the lake bottom elevation. [Please see these clarifications below and in the revised manuscript P11L3-8]

"The inner structure of the soil matrix beyond the 1941 breach bottom of Lake Palcacocha's moraine is unknown. Novotny and Klimes (2014) estimate that Lake Palcacocha's moraine bedrock might include granitic/sedimentary structures, though the depth at which those bedrock structures lie is not measured. If sampled soils stratification is constant through the moraine, no bedrock should exist above the lake bottom, reinforcing the no bedrock hypothesis and worst breach scenario adopted in this study."

Comment #11

How does change compaction of the material its erodability? It is clear that with greater depth the material will be compacted, moreover, it seems that the moraine which is now forming the lake dam was basal moraine of the glacier, thus could be compacted by its weight.

Response #11

We agree with this comment and rewrote the pointed paragraph [Please see these clarifications below and in the revised manuscript P11L9-23]

"The profile of the Lake Palcacocha moraine (Figure 3) exhibits three elevation layers associated with different moraine dimensions and impounded water volumes. These specific elevation layers represent major morphologic changes in the moraine profile. As the depth of moraine increases, moraine slope decreases, allowing higher DWH ratios to lie at deeper layers. Under this morphologic setting, shallower layers are more susceptible to fail than deeper layers. The surface of the upper layer (0 m to 22.5 m depth) seems more susceptible to erosion because it is immediately exposed to water flow and the length of a potential breach (699 m) at that level is about 285 m shorter than that of the full depth of the moraine, making the material to remove significantly lower. In terms of compaction and cohesion, these shallowest moraine layers are not necessarily less consolidated; before glacier retreat started, the moraine forming the lake dam was basal moraine of the glacier and might have been compacted by the total supported weight, at least at the proximal face of the moraine. 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 16.9×10^6 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."

Comment #12

[The profile of the Lake Palcacocha moraine (Fig. 3) exhibits three elevation layers associated with different moraine dimensions and impounded water volumes] Why did you choose these specific elevation layers?

Response #12

These specific elevation layers represent major morphologic changes in the moraine profile (Figure 3). As the depth of moraine increases, moraine slope decreases, allowing higher width-to-height (DWH) ratios for the deeper layers. Under this morphologic setting, shallower layers are more susceptible to erosion than deeper layers. [Please see these clarifications below and in the revised manuscript P11L9-23]

"The profile of the Lake Palcacocha moraine (Figure 3) exhibits three elevation layers associated with different moraine dimensions and impounded water volumes. These specific elevation layers represent major morphologic changes in the moraine profile. As the depth of moraine increases, moraine slope decreases, allowing higher DWH ratios to lie at deeper layers. Under this morphologic setting, shallower layers are more susceptible to fail than deeper layers. The surface of the upper layer (0 m to 22.5 m depth) seems more susceptible to erosion because it is immediately exposed to water flow and the length of a potential breach (699 m) at that level is about 285 m shorter than that of the full depth of the moraine, making the material to remove significantly lower. In terms of compaction and cohesion, these shallowest moraine layers are not necessarily less consolidated; before glacier retreat started, the moraine forming the lake dam was basal moraine of the glacier and might have been compacted by the total supported weight, at least at the proximal face of the moraine. 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 16.9×10^6 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."

Comment #13

Reasoning for this worst case scenario seems to me odd and not convincing. It seems that the authors have no information about the material of this specific moraine, and they also found no comparable cases in literature (which I questioned in one comment above) in terms of moraine dam breach morphology/size. Lacking any limits, authors consider almost everything to be possible. Such an approach does not seem acceptable for me. Also considering the fact that the worst case scenario exceeds the historical event. I think, there should be good theoretical reasoning supporting that moraine dam of such morphology may have breach to the suggested extend. For that, you should be able to reasonably explain/define process triggering such a massive breach. If you are not able to do it, I think you should find other way to define worst case scenario

Response #13

The worst breach scenario we are defining for the Lake Palcacocha moraine derives from the 1941 historical event. Since 1941, Lake Palcacocha evolved in such a way that a new setting of the lake and moraine emerged behind the remains of the old moraine. Regardless of the apparent morphological stability provided by the DWH ratios, the 1941 moraine failure virtually drained all of the impounded lake behind it (leaving something like 0.5×10^6 m^3), creating a breach that is still in place (Figure 2). The massive failure of this moraine in 1941 might indicate that the moraine morphology—apparently stable—is not driving its likelihood to fail. In contrast, hydraulic and geotechnical parameters do seem to dominate the stability conditions of the whole moraine. High DWH ratios are recurrent in moraine dams in the Cordillera Blanca. Qualitative, semi-quantitative, and quantitative assessments of the potential for outbursts in this area conclude that, despite their high DWH ratios, Lakes Quitacocha, Checquiacocha, Palcacocha, and Llaca are susceptible to outburst (Emmer and Vilímek, 2013). These assessments consistently identify Lake Palcacocha as one of the glacial lakes most prone to GLOF in the region. [Please see these clarifications below and in the revised manuscript P7L9-26]

"Since 1941, Lake Palcacocha evolved in such a way that a new setting of the lake and moraine emerged behind the remains of the old moraine. During the catastrophic 1941 flood, the breach downcutting stopped as the lake was getting empty and the water level approached the lake bottom. That lake bottom and, indeed, the whole coupled system of moraine and lake were different to what exists now. Fig. 3 reveals a profile running along Lake Palcacocha and its current moraine (derived from a 5 m DEM by the Ministry of Environment of Peru) (Horizons, 2013), and a reconstruction of the moraine profile before 1941 (projected from non-breached adjacent portions of the end moraine). Palcaraju Glacier has continued retreating, allowing the lake to deepen and grow upglacier, so that the bottom of the breach left by the 1941 GLOF is now the front of the current moraine (Fig. 3). Satellite images from ASTER mission (Fig. 4) illustrate the acceleration of those retreat-induced changes over the last decade, showing the predominant retreat direction of Palcaraju Glacier and the growth trend of Lake Palcacocha. For instance, by 2012 the lake had approximately doubled the length it exhibited in 2000, moving its deepest point towards north-east. The deepest point of the lake in the 2009 survey (≈ 70 m) was not even within the domain of Lake Palcacocha in 1941. As a result, the dimensions and shape of both the lake and moraine have changed; as the volume of Lake Palcacocha has increased ($14x10^6$ m^3 in 1941 to $17.2x10^6$ m^3 in 2009), the DWH of the moraine also increased from 6.3 to 14.9."

Moreover, the inner structure of the soil matrix beyond the 1941 breach bottom is unknown. Although Novotny and Klimes (2014) estimate that Palcacocha's moraine base might include granitic/sedimentary structures, the depth at which those structures might lie remains unknown. If sampled soils stratification is constant through the moraine, no bedrock should exist above the lake bottom, reinforcing a full depth failure as the worst case scenario. [Please see these clarifications below and in the revised manuscript P11L3-8]

"The inner structure of the soil matrix beyond the 1941 breach bottom of Lake Palcacocha's moraine is unknown. Novotny and Klimes (2014) estimate that Lake Palcacocha's moraine bedrock might include granitic/sedimentary structures, though the depth at which those bedrock structures lie is not measured. If sampled soils stratification is constant through the moraine, no bedrock should exist above the lake bottom, reinforcing the no bedrock hypothesis and worst breach scenario adopted in this study."

Additionally, the breach scale we are addressing, requiring erosion and movement of large masses of moraine material, is not uncommon in the history of GLOFs. The 1941 Palcacocha GLOF itself formed a breach through the moraine dam with total lengths over 500 m (Figure 3). Queen Bess Lake and Lake Cerro Largo, in the Patagonian Andes represent special cases of partial moraine failures, where the presence of bedrock within the moraine dams was the only factor preventing their total collapse, making further downcutting practically impossible (Clague and Evans, 2000). [Please see these clarifications below and in the revised manuscript P10L27-P11L2]

"The 1941 Palcacocha GLOF itself formed a breach through its moraine dam with a total length over 500 m (Figure 3). Queen Bess Lake and Lake Cerro Largo, despite their large magnitude breaches, represent rare cases of *partial moraine failure*, where a relevant factor preventing deepest breaches and total collapse was the presence of bedrock within the moraine dams, making further downcutting practically impossible (Clague and Evans, 2000)."

Comment #14

[Discharge from the moraine will progressively enlarge the downstream channel until the breach intersects the bottom of the second layer] How did you get information (probably new findings) in this paragraph? This is "Study area" chapter, but this information seems as results. Please add references or move to the result part with explaining relevant methodology.

Response #14

We rephrased the paragraph to point out relevant morphological information of the breach left by the 1941 GLOF in Palcacocha, presenting it as interpretation of existing information rather than as results. [Please see these clarifications below and in the revised manuscript P12L20-P13L2]

"The post-1941 morphology of Lake Palcacocha moraine (Figure 3) indicates that the outflow drained through the breach in 1941 progressively enlarged the downstream channel until the breach reached its maximum depth. By considering moraine erosion as a backward process (moving from the downstream face to the upstream face of the moraine), the shape of a maximum potential breach (Figure 6a) should reach its maximum dimensions at the breached-channel segments close to the front toe of the moraine prior to extending backward along the whole channel. A new GLOF event could reshape the current channel left by the 1941 breach, thus the initial dimensions of a new breach would adopt the dimensions of the current breach. Based on DEM analysis (Horizons, 2013), the 1941 breach had a bottom width of 50 m, slopes of 1:1 vertical to horizontal, and a depth of 56 m at the front toe of the moraine. This shape propagated backwards forming the breach channel. Under this setting, a new GLOF might potentially create a new breach, starting as a deeper extension of the 1941 GLOF channel (overlaid cross sections represented by dashed lines in Figure 6b)."

Comment #15

These empirical models do not solve a question, if the defined extend of the breach in this article is possible or not.

Response #15

We provide additional information on morphology of the moraine, pre- and post-1941 settings of lake and moraine, and geotechnical data regarding the soil matrix of the moraine, supporting the hypothesis of absence of bedrock (Responses #5 and #13). Moreover, we are contrasting morphological likelihood of failure identified in the literature for the Swiss Alps and the Himalayas with the characteristics of the Lake Palcacocha moraine. This comparison indicates that, regardless of the apparent morphological stability provided by its DWH ratios, the 1941 Lake Palcacocha moraine failure virtually drained all of the impounded lake behind it (leaving something like 0.5×10^6 m^3), creating a breach that is still in place (Figure 2). The massive failure of this moraine in 1941 might indicate that the moraine morphology—apparently stable—is not driving its likelihood to fail. Please also see descriptions of large breach events in Response #13 and below and in the revised manuscript on P11L24-P12L11.

"Regardless the apparent morphological stability provided by its DWH ratios, the Palcacocha moraine virtually drained all of the impounded lake water behind it in 1941 (leaving something like 0.5×10^6 m^3,), creating a breach that is still in place (Figure 2). The massive failure of this moraine in 1941 might indicates that the moraine morphology—apparently stable—is not driving its likelihood to fail. In contrast, hydraulic, freeboard, and geotechnical parameters do seem to dominate the stability conditions of the whole moraine. High DWH ratios are recurrent in moraine dams in the Cordillera Blanca. Qualitative, semi-quantitative, and quantitative assessments on potential for outbursts in this area estimate that, despite their high DWH ratios, Lakes Quitacocha, Checquiacocha, Palcacocha, and Llaca are susceptible to outbursts (Emmer and Vilímek, 2013) because of susceptibility factors like proximity between lake and glacier tongue, icefall or landslide likelihood, or short moraine freeboards. These assessments consistently identify Lake Palcacocha as one of the glacial lake settings most prone to GLOFs in the region, as long as a trigger event (e.g., an avalanche in the form of an icefall, rockfall, or rock avalanche) creates an overtopping wave, favoring continuous further erosion of the front end of the moraine. Without this overtopping wave, current drainage structures prevent the water level from exceeding the current 8 m freeboard, preventing any flow over the moraine dam. Although this study only addresses the second phase of a two-phase process of overtopping wave and moraine failure, it recognizes the dependency between both phenomena and does not suggest that, in terms of hazard, one phenomenon dominates over the other."

Comment #16

[…in the case of Lake Palcacocha, where the geotechnical characteristics of the moraine are mostly unknown] Please state those, which are known.

Response #16

The only available data correspond to shallow soil samples, whose composition indicates that lower elevation soils (close to the toe of the moraine) consist of well-graded gravel, silty gravel, or clayey gravel, while finer soils predominate at higher layers of the moraine, including clayey sand or silty sand (Novotny and Klimes, 2014). [Please see these clarifications below and in the revised manuscript P18L18-22]

"The only available data correspond to shallow soil samples, whose composition indicates that lower elevation soils (close to the toe of the moraine) consist of well-graded gravel, silty gravel, or clayey gravel, while finer soils predominate at higher layers of the moraine, including clayey sand or silty sand (Novotny and Klimes, 2014)."

Comment #17

[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] I deeply disagree with this statement. You provided no data or information which may be used for objective or independent validation of the gained results, therefore there is no reason to think that the applied approach is useful at all.

Response #17

We do not provide data for independent validation. The core idea behind the approach we propose is that we lack independent data for validation, as is the case in most remote areas where glacial lakes exist and this approach might apply. Instead, we propose that it is possible to evaluate the suitability of empirical models by verifying that the produced results are hydraulically realistic (i.e., outflow results do not deviate from the conveyance capacity of the defined breach). This kind of assessment is a step forward in empirical model application for dam breach failures. The approach is not an integral solution for dam breach problems since it is supported solely by hydraulic modeling. Geotechnical information only supports the no-bedrock hypothesis and poor cohesion description of the soil matrix from a qualitative point of view. However, the results do rely on physical properties of the problem (lake and moraine interaction to produce outflow), rather than only on statistical parameters or individual comparison of lake and moraine characteristics. [Please see these clarifications below and in the revised manuscript P19L10-21]

"We do not provide data for independent validation. The core idea behind the approach we propose is that we lack independent data for validation, as is the case in most remote areas where glacial lakes exist and this methodology might apply. Instead, we propose that it is possible to evaluate the suitability of empirical models by verifying that the produced results are hydraulically realistic (i.e., outflow results do not deviate from the conveyance capacity of the defined breach). This kind of assessment is a step forward in empirical model application for dam breach failures. The approach is not an integral solution for dam breach problems, since it is supported solely by hydraulic modeling. Geotechnical information only supports the no-bedrock hypothesis and poor cohesion description of the soil matrix from a qualitative point of view. However, the results do rely on physical properties of the problem (lake and moraine interaction to produce outflow), rather than only on statistical parameters or individual comparison of lake and moraine characteristics."

Comment #18

[A new method has been presented for extending prior empirical models that provide only peak flows and failure times for a dam break] I have doubts, if the article presents a new method

(Conclusions are the first place you use this term, before you used "approach"), since you just combined two (in the case of empirical models several) already existing methods.

Response #18

We accept the suggestion. “Approach” is the proper term and it is used consistently in the revised manuscript.

Comment #19 and # 20

[The method succeeds on providing first hydrograph estimations that can support risk assessment studies in remote locations]. I do not agree with this.

[Likewise, it sets criteria to evaluate the quality of those estimations] No relevant criteria have been defined.

Response #19 and #20

We agree with both comments and the manuscript as been revised to reflect these comments. [Please see these clarifications below and in the revised manuscript P20L14-22]

“A new approach has been presented for extending prior empirical models that provide only peak flows and failure times for a dam break. Following this new approach, it is possible to determine the maximum and minimum flow hydrographs that are consistent with the empirical model. The resulting approach 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 approach could be adapted to any unsteady-flow hydraulic simulation method. The advantage of the approach is that it provides a simple way to estimating a hydrograph for potential dam breaks where data are limited, which is the case for many glacial lakes that endanger downstream populations.”

Anonymous Referee #2

Dear Referee:

We appreciate your interest on this work and share your concerns about clarifying arguments that support the worst-case scenario we are proposing, and to provide better explanations on dam features and characteristics, as well as a description of previous GLOF events at Lake Palcacocha (1941).

We understand that underestimating future dam failures might result in ineffective mitigation actions, exposing people to severe danger. On the other hand, we also recognize that overestimating their magnitude might lead to creating an atmosphere of fear in communities that, otherwise, also depend on water resources coming from glaciers. This version of the manuscript represents a major revision, aiming to address common comments we received from you and other NHESS readers pointing out the worst-case scenario definition as a critical issue to carefully address.

The general structure of the document is now different to favor introducing the suggested changes:

1. Introduction
2. Study Area
3. Methodology
   - 3.1 Overview
   - 3.2 Worst breach scenario: a link in a chain of GLOF processes
   - 3.3 Peak Flow and Failure Time Estimation
   - 3.4 Dam Breach Hydraulic Simulation
   - 3.5 Assessment of Empirical Equation Performance
   - 3.6 Model Selection and Probabilistic Assessment
4. Results and Discussion
   - 4.1 Comparison of Empirical Models
   - 4.2 Comparison of Empirical and DAMBRK Model Results
   - 4.3 Limitations and Advantages
5. Conclusion

Deeper explanations of the changes in the paper appear below, according to your comments, indicating the location of each change in the revised manuscript.

Best regards

The Authors

Comment #1

The first question to the Authors is why do they assume that a breach of the dam might be more likely than overtopping? Personally, I am not convinced at all that dam breach might be the most likely scenario. On the other hand, overtopping caused by a slope movement in the lake could be an alternative, whilst dam breaching only a secondary effects (likely, with minor floods than that caused by overtopping). This is an important point for the whole article, and should be carefully clarified to justify the choice of your worst-case scenario.

Response # 1

We realize the term "worst-case" scenario can lead to a general misunderstanding; changes in this version of the manuscript aim to resolve this issue. This paper seeks to explore and propose ways to estimate outflow hydrographs produced by a possible moraine collapse at Lake Palcacocha. This collapse event, however, is not independent; a prior event such as a landslide or icefall would be needed to initiate a chain of processes leading to a partial or total moraine failure. In Section 3.2 of the revised manuscript (Worst breach scenario: a link in a chain of GLOF processes), we describe this two-phase process, which starts with (1) a mass of material (avalanche, icefall, or landslide) falling into the lake, creating a wave that runs up and quickly overtops the moraine, and whose erosive power induces (2) a progressive collapse of this impounding moraine, leading to a slower release of lake water to the downstream valley.

The collapse or failure of the moraine is the second part of this two-phase process. In this context, we refer to worst breach scenario as the maximum potential hydrograph derived exclusively from a massive, erosive moraine failure. We recognize that overtopping waves by themselves, independently of further moraine collapse, may create a GLOF whose peak flows might equal or exceed those of an erosive failure. However, at Lake Palcacocha, there is no evidence to suggest that a flood produced only by overtopping waves might create higher hazards than the further erosion-collapse of the moraine. Although we are only approaching the second phase of the two-phase process of overtopping wave and moraine failure, we are not suggesting that, in terms of hazard, one process dominates over the other. [Please see these clarifications below and in the revised manuscript P11L24-P12L11].

"Regardless the apparent morphological stability provided by its DWH ratios, the Palcacocha moraine virtually drained all of the impounded lake water behind it in 1941 (leaving something like $0.5x10^6$ m^3,), creating a breach that is still in place (Figure 2). The massive failure of this moraine in 1941 might indicates that the moraine morphology—apparently stable—is not driving its likelihood to fail. In contrast, hydraulic, freeboard, and geotechnical parameters do seem to dominate the stability conditions of the whole moraine. High DWH ratios are recurrent in moraine dams in the Cordillera Blanca. Qualitative, semi-quantitative, and quantitative assessments on potential for outbursts in this area estimate that, despite their high DWH ratios, Lakes Quitacocha, Checquiacocha, Palcacocha, and Llaca are susceptible to outbursts (Emmer and Vilímek, 2013) because of susceptibility factors like proximity between lake and glacier tongue, icefall or landslide likelihood, or short moraine freeboards. These assessments consistently identify Lake Palcacocha as one of the glacial lake settings most prone to GLOFs in the region, as long as a trigger event (e.g., an avalanche in the form of an icefall, rockfall, or rock avalanche) creates an overtopping wave, favoring continuous further erosion of the front end of the moraine. Without this overtopping wave, current drainage structures prevent the water level from exceeding the current 8 m freeboard, preventing any flow over the moraine dam. Although this study only addresses the second phase of a two-phase process of overtopping wave and moraine failure, it recognizes the dependency between both phenomena and does not suggest that, in terms of hazard, one phenomenon dominates over the other."

Comment #2 – The 1941 breach

Authors briefly refer to the 1941 breach (saying that "it still exists", page 5981) but do not provide any description of it, in terms of morphology, morphometry, where it is located, etc. Further, no information is provided about the 1941 breach: why and how did it occur? What data are available about that event? And, were some remedial works performed after that breach, or was the situation left as produced by the breach itself? What consequences had the 1941 breach in terms of risk to population (that is, where did the flood arrive downstream)?

Response # 2

In 1941 the lake bottom and, indeed, the whole coupled system of moraine and lake was different. The lake bottom in 1941 was above the current bottom of the lake. Since 1941 the lake grew vertically and longitudinally (upglacier) due to glacier retreat (Fig. 3). Today's deepest point of the lake (≈ 70 m) was not even within the domain of Lake Palcacocha in 1941. [Please see these clarifications below and in the revised manuscript P7L9-26, including the analysis of Fig. 4 (see above in Response to Adam Emmer), which shows the growth trend of Lake Palcacocha over the last two decades].

"Since 1941, Lake Palcacocha evolved in such a way that a new setting of the lake and moraine emerged behind the remains of the old moraine. During the catastrophic 1941 flood, the breach downcutting stopped as the lake was getting empty and the water level approached the lake bottom. That lake bottom and, indeed, the whole coupled system of moraine and lake were different to what exists now. Fig. 3 reveals a profile running along Lake Palcacocha and its current moraine (derived from a 5 m DEM by the Ministry of Environment of Peru) (Horizons, 2013), and a reconstruction of the moraine profile before 1941 (projected from non-breached adjacent portions of the end moraine). Palcaraju Glacier has continued retreating, allowing the lake to deepen and grow upglacier, so that the bottom of the breach left by the 1941 GLOF is now the front of the current moraine (Fig. 3). Satellite images from ASTER mission (Fig. 4) illustrate the acceleration of those retreat-induced changes over the last decade, showing the predominant retreat direction of Palcaraju Glacier and the growth trend of Lake Palcacocha. For instance, by 2012 the lake had approximately doubled the length it exhibited in 2000, moving its deepest point towards north-east. The deepest point of the lake in the 2009 survey (≈ 70 m) was not even within the domain of Lake Palcacocha in 1941. As a result, the dimensions and shape of both the lake and moraine have changed; as the volume of Lake Palcacocha has increased ($14x10^6$ m^3 in 1941 to $17.2x10^6$ m^3 in 2009), the DWH of the moraine also increased from 6.3 to 14.9."

We have added a deeper analysis of pre- and post-1941 moraine morphology in this revised version of the manuscript. Figure 3 suggests that, as a result of glacier retreat, the dimensions

and shape of both the lake and moraine changed after 1941; as Lake Palcacocha's volume grew ($14x10^6$ m^3 in 1941 to 17.2 $x10^6$ m^3 in 2009), the width-to-height ratio (DWH) of the moraine also increased from 6.3 to 14.9. The need of an overtopping wave to induce further erosion failure recognizes that current drainage structures and remedial works prevent flow over the dam unless a trigger event generates such a wave. Hence, erosion independent events are unlikely to completely collapse the moraine dam of Lake Palcacocha. However, at Lake Palcacocha, there is no evidence to suggest that a flood produced only by overtopping waves might create higher hazards than the further erosion-collapse of the moraine. Although we are only approaching the second phase of the two-phase process of overtopping wave and moraine failure, we are not suggesting that, in terms of hazard, one process dominates over the other.
[Please see the response to Comment #2 of Adam Emmer above.]

Regardless the apparent morphological stability provided by the DWH ratios, the Lake Palcacocha moraine virtually drained all of the impounded lake water behind it in 1941 (leaving something like $0.5x10^6$ m^3), creating a breach that is still in place (Figure 2). The massive failure of this moraine in 1941 might indicate that the moraine morphology—apparently stable—is not driving its likelihood to fail. In contrast, hydraulic and geotechnical parameters do seem to dominate the stability conditions of the whole moraine. High DWH ratios are recurrent in moraine dams in the Cordillera Blanca. Qualitative, semi-quantitative, and quantitative assessments on potential for outbursts in this area estimate that, despite their high DWH ratios, Lakes Quitacocha, Checquiacocha, Palcacocha, and Llaca are susceptible to outbursts (Emmer and Vilímek, 2013). These assessments consistently identify Lake Palcacocha as one of the glacial lake settings most prone to GLOFs in the region. [Please see the response to Comment #1 of Anonymous Reviewer #1 above and in the revised manuscript P11L24-P12L11]

Comment #3 – Dam Features

Too many assumptions are presented when describing the moraine dam: for instance, it is assumed that "the degree and compaction of the shallowest moraine layers is likely to be lower than that of deeper layers" (page 5981), but no data are given to support this. Dam geometry and physical properties should be considered when hypothesizing a possible scenario for dam breaching or overtopping. They are not dealt with in the manuscript, and this needs to be corrected in some ways.

Response # 3

There are few geological or geotechnical studies of the current composition of the Lake Palcacocha 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 (Novotny and Klimes, 2014). The moraine front surface at Lake Palcacocha currently exhibits what was the 1941 breach bottom. The differences between soil matrices at the rear and front zones of that breach channel, as well as at the crest of the moraine prior to 1941, reveal the heterogeneous and stratified structures composing Lake Palcacocha's moraine. Lower elevation soil samples (shallow samples at depths of 0.1 m below the breach surface) are generally coarser (well-graded gravel, silty gravel, or clayey gravel) than those of higher layers of the same moraine, where clayey sand or silty sand soils predominate (Novotny and Klimes, 2014). [Please see the response to Comment P5981L20 of Adam Emmer above and in the revised manuscript P6L28-P7L8]

The inner structure of the soil matrix beyond the 1941 breach bottom is unknown. Novotny and Klimes (2014) estimate that Lake Palcacocha's moraine bedrock might include granitic/sedimentary structures, though the depth at which those bedrock structures lie is not measured. If the sampled soil stratification is constant through the moraine, no bedrock should exist above the lake bottom elevation. [Please see response to Comment P5981L20 of Adam Emmer above]

Additionally, we have rewritten the cited paragraph. [Please see these clarifications below and in the revised manuscript P11L9-23]

"The profile of the Lake Palcacocha moraine (Figure 3) exhibits three elevation layers associated with different moraine dimensions and impounded water volumes. These specific elevation layers represent major morphologic changes in the moraine profile. As the depth of moraine increases, moraine slope decreases, allowing higher DWH ratios to lie at deeper layers. Under this morphologic setting, shallower layers are more susceptible to fail than deeper layers. The surface of the upper layer (0 m to 22.5 m depth) seems more susceptible to erosion because it is immediately exposed to water flow and the length of a potential breach (699 m) at that level is about 285 m shorter than that of the full depth of the moraine, making the material to remove significantly lower. In terms of compaction and cohesion, these shallowest moraine layers are not necessarily less consolidated; before glacier retreat started, the moraine forming the lake dam was basal moraine of the glacier and might have been compacted by the total supported weight, at least at the proximal face of the moraine. 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 $16.9x10^6$ 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."

Comment #4 – Conclusions

The worst-case scenario taken into account by the Authors is not justified by actual data (or, at least, these are not presented in the manuscript). Authors should not forget the social implications of such a work, since the risk to downstream towns is an issue to be treated very carefully, and based on real data to support the choice of both the scenario and the model used. For all the above points, I recommend a major revision of the manuscript, looking forward to integration and clarification in the revised version to reply to the doubts and questions presented here.

Response # 4

In the above responses we are adding deeper data and explanations (referred to specific sections of the document) to support the choice of a **worst moraine failure;** those explanations focus on geomorphology and geotechnical parameters of the Lake Palcacocha Moraine, pre- and post-1941, coupled lake/moraine characteristics, and comparisons with similar-magnitude events worldwide. For instance, we are highlighting that the breach scale we are addressing, requiring erosion and movement of large moraine masses, is not uncommon in the history of GLOFs. In 1997 an ice avalanche over Queen Bess Lake (Canada) produced overtopping waves that started a breaching process of the moraine dam. The resulting breach reached lengths over 600 m and depths between 15-25 m, releasing $8x10^6$ m^3 of impounded water; Nostetuko Lake (Canada) suffered the same kind of two-phase GLOF in 1983, which created a massive breach failure (480 m-length and 40 m-depth) (Clague and Evans, 2000). In South America, Lake Cerro Largo (Patagonian Andes) experienced a GLOF in 1989 draining $24.73x10^6$ m^3 from the lake, carving a 500 m long breach; a more recent GLOF in the Patagonian Andes region discharged $10x10^6$ m^3 (4100 m^3/s) from Lake Ventisquero Negro in 2009, eroding a 350 m long breach with depths up to 50 m (Clague and Evans, 2000; Worni et al., 2012). The 1941 Palcacocha GLOF itself formed a breach through the moraine dam with a total length over 500 m (Fig. 3). Queen Bess Lake and Lake Cerro Largo, despite their large magnitude breaches, represent special cases of partial moraine failure, where the presence of bedrock within the moraine dams prevented their total collapse, making further downcutting practically impossible (Clague and Evans, 2000). [Please see these clarifications below and in the revised manuscript P10L8-P11L2]

"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 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. This breach scale, requiring erosion and movement of large moraine masses, is not uncommon in the history of GLOFs. In 1997 an ice avalanche over Queen Bess Lake (Canada) produced overtopping waves that started a breaching process of the moraine dam. The resulting breach reached lengths over 600 m and depths between 15-25 m, releasing $8x10^6$ m^3 of impounded water; Nostetuko Lake (Canada) suffered the same kind of two-phase GLOF in 1983, which created a massive breach failure (480 m-length and 40 m-depth) (Clague and Evans, 2000). In South America, Lake Cerro Largo (Patagonian Andes) attracts attention because a GLOF in 1989 drained $24.73x10^6$ m^3 out of the lake, carving a 500 m length breach; a more recent GLOF in the Patagonian Andes region discharged $10x10^6$ m^3 (4100 m^3/s) from Lake Ventisquero Negro in 2009, eroding a 350 m length breach with depths up to 50 m (Clague and Evans, 2000; Worni et al, 2012). In 1998 a GLOF eroded the moraine dam of Tam Pokhari Lake (Mt. Everest region of Nepal), releasing a water volume of $18x10^6$ m^3; the resulting breach length exceeded 500 m, with an average width and height of 60 m and 50 m (Osti and Egashira, 2009). The 1941 Palcacocha GLOF itself formed a breach through its moraine dam with a total length over 500 m (Figure 3). Queen Bess Lake and Lake Cerro Largo, despite their large magnitude breaches, represent rare cases of *partial moraine failure*, where a relevant factor preventing deepest breaches and total collapse was the presence of bedrock within the moraine dams, making further downcutting practically impossible (Clague and Evans, 2000)."