

Response to review comments on Huggel et al: Anthropogenic climate change and glacier lake outburst flood risk: local and global drivers and responsibilities for the case of Lake Palcacocha, Peru.

We generally would like to express to acknowledge the review comments and suggestions made by the two reviewers and the additional comments contributed by colleagues. We appreciate the time our colleagues have taken to read and analyze the paper, especially during the current difficult times. We found all comments helpful and suggestions constructive and are very positive that we can appropriately address all points.

In the following, review comments are in normal font and our response is in italic.

Response to review comments by Dmitry Petrakov

General comments: The Lake Palcacocha was a source of the most destructive GLOF in human history which happened in 1941. Some mitigation measures to prevent lake outburst have been done. Growing volume of the lake due to glacier retreat is accompanying by growing population of Huaraz city located at the flow path. Thus any attempts to assess risk of GLOF from the Lake Palcacocha are highly relevant both at local and global scale. Authors used the Lake Palcacocha as a representative case for other glacier lakes and related risks around the world. The paper provides high-quality case study with significant conclusions, both locally and globally. It also provides nice synthesis of natural and social sciences which is important for comprehensive risk assessments.

Novelty of results is quite clear. Structure of the paper is reasonable, Introduction is well-written, motivation and goals of the paper are fully clear. Authors provide brief but comprehensive description of the Lake Palcacocha evolution and engineering solutions to prevent dam failure. Currently lake growth potential is limited by topographic constraints, but outburst probability is high. Authors analyzed anthropogenic contribution to glacier retreat in Cordillera Blanca based on literature review and concluded that growth of lake Palcacocha has a clear anthropogenic signal. GLOF hazard in the absence of anthropogenic climate change the flood hazard would be much lower due to change of lake volume and increasing impact energy of ice/rock avalanches. Socio-economic drivers of risk are determined and analyzed basing on literature review and survey conducted in 2017. What is important, local residents showed little concern for the risk of flooding. The institutional instability generated only short-term, unsustainable measures to protect downstream populations. Authors note that combined effects of institutional and governance-related risk drivers have contributed to the increase of risk and provide interesting insight on cultural and emotional component of risk. Basing on analysis of risk drivers authors provide implications for responsibility and justice.

The manuscript is well written and free of technical errors, well structured, appropriate in length. All figures and the table are high-quality. Supplementary material is very useful for understanding of hazard assessment technology. The conclusions are clear and precise. The results obtained in this study are highly relevant to assess risk of future GLOFs not just in Huaraz but elsewhere. I definitely support publication of the manuscript.

Author response:

Thanks for this analysis of the study and appreciation of our work.

Specific comments:

Authors noted that previous studies estimated about 40,000 people living in the inundation zone with a potential death toll of close to 20,000 (Somos-Valenzuela, 2014).

Anywhere there is no assessment of current situation despite Fig.7 demonstrates significant growth of population in Huaraz. How many people live in zones with different hazard level (Fig.5) now? Is population density within hazardous area uniform or not? An addition of a figure where population density will be provided solely or overlaid to hazard zonation might be interesting for readers and

useful for local communities and decision makers. Being fully agree with author's concept I will be happy to see what components of risk are major and what components are really minor. Furthermore, some recommendation how to minimize GLOF risk in Huaraz basing on risk driver analysis will increase practical and intellectual merit of this really great paper.

Thanks for pointing out these aspects.

We were investigating digital data on population distribution in Huaraz, and thanks to our colleague Marcelo Somos-Valenzuela were able to get access to pertinent GIS based data from the National Statistical Institute INEI which allowed us to perform additional analysis to address Dmitry Petrakov's comments and suggestions. This analysis which is supported by a new figure indicates that high population density intersects with the high hazard zone. We carefully evaluated how we could best graphically represent the different information layers in one figure such that the reader could quickly infer hazard zones vs population density. A full overlay of population distribution data, with hazard zones and underlying satellite data is not feasible, therefore, for reasons of visual clarity we include now two panels in Figure 5. Nevertheless, we indicate the extent of the high hazard zone in the population distribution map such that the reader can quickly grasp the relevant information.

However, in terms of risks we also add here a word of caution: population data only refers to residential population, but the GLOF risk threatens parts of the city center, including markets, business centers,, touristic attractions, bus stations, etc., which can have much higher concentration of people, depending on daytime. And eventually, the death toll is very difficult to estimate because death depends on multiple factors such as detailed structural building data, physical conditions of people depending on additional factors such as age, health conditions, daytime (see above) etc. We don't think we're in a position to perform such as estimate of death toll and therefore mention the estimate given by Somos-Valenzuela (2014).

We include results of all this additional analysis in section 3 of the paper (physical drivers of risk), and the revised text section is now as follows:

"Previous studies estimated about 40,000 people living in the inundation zone with a potential death toll of close to 20,000 (Somos-Valenzuela, 2014). Based on spatial census data from the National Statistical Institute of Peru (INEI), here we found that about 22,500 inhabitants living in the high hazard zone are highly exposed to GLOF (Fig. 5). However, because the high hazard zone intersects with the central business and market places of Huaraz the number of people present during the day times is much higher, possibly up to 50,000."

Additionally, in the Supplementary Material, we slightly revised the text explaining in further detail the method to generate the hazard zones in Huaraz. We specify that we use a threshold of 1 m inundation height to distinguish between medium and high intensity zones which are then converted into hazard zones in line with international standards.

The point about an evaluation of major and minor components of risk is a very interesting one but at the same time also very challenging to perform in the absence of a fully quantitative risk analysis across all different risk drivers. It is important to consider that risk is a function of hazard, exposure and vulnerability, and hence, if there is no hazard or no exposure no risk exists. So one could argue that without the existence of Lake Palcacocha (or other glacier lakes above Huaraz including Shallap, Cuchillacocha, Tulparaju, and Llaca) no GLOF risk in Huaraz would exist. Likewise if there were no exposed assets such as people, homes, infrastructure, or agriculture, then no (or minimal) GLOF risk would exist. We think that the question of major vs minor risk components can only be appropriately

addressed if different risk components are weighted, which, eventually is a societal or political question. For instance, is a building or a human life weighted higher? We would like to abstain from weighting different risk components, and hence we would not be in a position to make a statement about major/minor risk components. However, we think it is an important discussion and we therefore include this issue in section 7.

Concerning recommendations for risk reduction measures we mention quite many different types of measures in section 7 when referring to different responsibilities but we now include also a short additional text section with related recommendations in section 8.

Response to review comments by Marcus Nüsser

Reviewer comment:

Based on the prominent case study of Lake Palcacocha in the Peruvian Andes the paper deals with the complexity of “socio-economical, institutional and cultural processes” which become drivers of risk exposure and vulnerability and ultimately shape glacier lake outburst flood risk for the urban agglomeration of Huaraz. Questions of associated responsibilities, causality, and justice in the context of the adverse effects of climate change are also raised. This integration of a “normative responsibility framework” is rather unusual and innovative in scientific studies on GLOFs. It extends the research perspective and integrates dimensions of political ecology and glaciology. The paper is very well structured and the line of argument is convincing throughout the text. The introduction presents a clear statement of the problem with relevant references.

Author response:

Thanks for this analysis.

Reviewer comments:

When the authors mention the “impacts of glacier changes on natural and human systems” (l 32) they might also refer to papers on socio-hydrological interactions in other mountain regions in order to strengthen the global perspective. There are a number of contributions from various parts of the Himalaya. Such references would also be useful when the authors refer to adaptation strategies to cope with cryosphere changes (l 40-44). Socio-hydrological case studies dealing with meltwater dependent irrigated agriculture may be useful in this context (e.g. from Ladakh).

Author response:

Yes, good point, we now include additional reference to studies of socio-hydrological interactions in the Introduction section of the paper, specifically we include several references with additional indications on international (incl Himalayas and Ladakh studies) studies on socio-hydrologic and socio-cryospheric research and emphasize the important progress that has been made in this field in recent years. We include the following additional references (included in the paragraph of lines 38-48).

Allison, E. A.: The spiritual significance of glaciers in an age of climate change, WIREs Climate Change, 6, 493-508, 2015.

Carey, M., McDowell, G., Huggel, C., Jackson, J., Portocarrero, C., Reynolds, J. M., and Vicuña, L.: Integrated Approaches to Adaptation and Disaster Risk Reduction in Dynamic Socio-cryospheric Systems, in: Snow and Ice-Related Hazards, Risks, and Disasters, edited by: Haeberli, W., and Whiteman, C., Elsevier, Amsterdam, 219-261, 2014.

Drew, G.: *A Retreating Goddess? Conflicting Perceptions of Ecological Change near the Gangotri-Gaumukh Glacier*, *Journal for the Study of Religion, Nature and Culture*, 6, 344-362, 2012.

Gagné, K.: *Caring for Glaciers: Land, Animals, and Humanity in the Himalayas*, University of Washington Press, Seattle, 2019.

Gagné, K., Rasmussen, M. B., and Orlove, B.: *Glaciers and Society: Attributions, Perceptions, and Valuations*, *WIREs Climate Change*, 5, 793-808, 2014.

Mukherji, A., Sinisalo, A., Nüsser, M., Garrard, R., and Eriksson, M.: *Contributions of the cryosphere to mountain communities in the Hindu Kush Himalaya: a review*, *Regional Environmental Change*, 19, 1311-1326, 2019.

Nüsser, M., and Baghel, R.: *The Emergence of the Cryoscape: Contested Narratives of Himalayan Glacier Dynamics and Climate Change*, in: *Environmental and Climate Change in South and Southeast Asia*, edited by: Schuler, B., Koninklijke Brill, Leiden, 138-156, 2014.

Nüsser, M., and Baghel, R.: *Local Knowledge and Global Concerns: Artificial Glaciers as a Focus of Environmental Knowledge and Development Interventions*, in: *Ethnic and Cultural Dimensions of Knowledge. Knowledge and Space*, edited by: Neusburger, P., Freytag, T., and Suarsana, L., Springer, Switzerland, 191-209, 2016.

Nüsser, M., Dame, J., Kraus, B., Baghel, R., and Schmidt, S.: *Socio-hydrology of "artificial glaciers" in Ladakh, India: assessing adaptive strategies in a changing cryosphere*, *Regional Environmental Change*, 19, 1327-1337, 2019.

Orlove, B., Milch, K., Zaval, L., Ungemach, C., Brugger, J., Dunbar, K., and Jurt, C.: *Framing climate change in frontline communities: anthropological insights on how mountain dwellers in the USA, Peru, and Italy adapt to glacier retreat*, *Regional Environmental Change*, 19, 1295-1309, 2019.

Sherry, J., Curtis, A., Mendham, E., and Toman, E.: *Cultural landscapes at risk: Exploring the meaning of place in a sacred valley of Nepal*, *Global Environmental Change*, 52, 190-200, 2018.

Sörlin, S.: *Cryo-History: Narratives of Ice and the Emerging Arctic Humanities*, in: *The New Arctic*, edited by: Evengård, B., Larsen, J. N., and Paasche, Ø., Springer, New York, 327-339, 2015.

Williams, C., and Golovnev, I.: *Pamiri Women and the Melting Glaciers of Tajikistan*, in: *A Political Ecology of Women, Water and Global Environmental Change*, edited by: Buechler, S., and Hanson, A.-M. S., Routledge, New York, chapter 11, 2015.

Reviewer comment:

The authors present their general understanding of this glacier riskscape "as a function of physical hazard, human exposure, and vulnerability of people and assets" (l 60), taking into consideration the IPCC-based framework and classical risk concepts developed by Blaikie, Oliver-Smith, and Wisner. The case of lake Palcacocha is particularly interesting as it is not only a representative case study for cryosphere risks (in the sense of the cryoscape) but it also presents a legal case where different actors are involved, in this case, a local Peruvian citizen and a German energy producer.

The case study of Lake Palcacocha is presented in a detailed and historically informed way. The physical and socio-economic drivers of risk are also presented in a convincing way. Section 4 provides important information on the socio-economic drivers of risk, especially the importance of recent urbanization processes, demographic growth, and the role of different actor groups (Quechua-speaking farmers,

mine workers, ruling Spanish-speaking classes) together with some remarks on settlement history. It is important to focus on class division, social marginalization and other economic factors to understand decision-making in urban planning and practices of building in hazard prone regions. The authors might also add some examples from other mountain regions in the Global South to have a wider and more global context (people opt for habitat locations in hazard-prone flood plains because of economic gains).

Author response:

Agreed, we now put the Palcacocha case in the context of other, potentially similar cases in developing countries, specifically, we make reference to cases, including in the Himalayas but also in other parts of the Andes, North America and Europe. We add a paragraph addressing this comment in section 6, on the cultural components of risk.

“These trends in the Cordillera Blanca also exist internationally, and people knowingly inhabit areas exposed to GLOFs in other glacier-fed watersheds. In some cases, they are “forced” into these areas due to cheaper land in the floodplain or nearby job and livelihood opportunities (Carey et al., 2014; Orlove et al., 2019). In other cases, they select GLOF-prone sites to live due to historical and cultural connections to those flood-prone places (Sherry et al., 2018), or they utilize other cultural or spiritual techniques to manage glacier-related risks (Allison, 2015; Gagné, 2019), or they possess different local knowledge about risk that sometimes differs from scientific or institutional assessments of GLOF risks (Drew, 2012; Williams and Golovnev, 2015). Furthermore, in India for example, there are also documented recent major GLOF disasters due to exposure and high vulnerability of a large number of people due to religious and tourism related reasons (Allen et al., 2016).”

Reviewer comment:

The last few lines of this section (l 299-300) are quite general (global histories of colonial power, neoliberalism, resource extraction). These aspects might be contextualized with social processes in the context of GLOF disasters.

Author response:

These two lines are intentionally quite general because these lines are at the end of the respective section 4 and they should summarize the points made in the above text of this section. But we believe to see Marcus Nüsser’s point and now modified the text at the end of this section to make more specific reference to the conditions in Huaraz.

Reviewer comment:

Section 5 provides detailed information on weak institutional structures and problems in regional governance over the past decades. The set of culturally embedded explanations of the 1941 GLOF and the important aspect of local concepts of place attachment are contextualized as other dimensions of explanation. The authors conclude that risk and associated loss and damage “is a multi-faceted construction and the question of causality can often not be fully solved, at least not in a quantitative way” (l 485-486). The paper uses a local case study to provide a multi-dimensional analysis with very relevant implications for international climate policy. This is innovative and deserves publication. The figures are relevant and illustrative.

Author response:

Comments and evaluation of our study appreciated.

Reviewer comment:

Some few typos need to be corrected, e.g. l 104 two punctuations l 115 Hans Kinzl l

136 delete one bracket.

Author response:

Thanks, we corrected these typos.

Response to short comment by Will Frank

The author of this note helped to prepare the legal arguments for Luciano Lliuya's lawsuit against RWE because of the endangerment of the plaintiff's home by a possible glacial outburst flood risk (GLOF) (see Frank, The Huaraz Case, Climate Law Blog, Sabin Center, Columbia Law School, posted Dec. 17th, 2017; available at: <http://blogs.law.columbia.edu/climatechange/2017/12/07/the-huaraz-case-lluiya-v-rwe-german-court-opens-recourse-to-climate-law-suit-against-big-co2-emitter/>).

A) Summary of Facts

The authors of the study make the following statements, among others:

1) The water volume of Lake Palcacocha has increased significantly since the late 1970s (line 130). The water levels have developed as follows: Volume 1974: 3,690 x 10.000.000 m³; Volume 2009: 17,325 x 10.000.000 m³; Volume 2016: 17,403 x 10.000.000 m³. The water level was lowered by 3 m in 2018. 2) Palcacocha is one of the glacial lakes where glacial flooding can be triggered by rapid landslide processes (line 145). 3) Available studies agree that temperatures in the Peruvian Andes, including the Cordillera Blanca, have risen since the 1960s at a rate of about 0.2 to 0.3 °C per decade and about 0.1 °C per decade over the last 30 years (line 175). 4) The anthropogenic greenhouse effect has been identified as the most probable cause of warming over time (line 178). 5) El Niño and La Niña and ENSO cannot explain the melting of glaciers over time (lines 186-187). 6) According to various studies, climate change clearly plays a significant role in the melting of glaciers. This assessment is in line with the IPCC, according to which the melting of the glaciers in the Andes is very likely ("very high confidence") to be attributable to climate change (line 190). 7) According to a study from 2014, two thirds of the loss of mass of the glaciers in the Andes can be explained by global warming (line 192). 8) Almost 100% of the increase in the water volume of Lake Palcacocha is due to the melting of the glacier (line 199). 9) The growth of Lake Palcacocha has a clear anthropogenic component ("signal") (line 204).

B) Remarks

The authors come on the basis of the aforementioned facts to the conclusion:

"It can be said with certainty that without anthropogenic climate change the danger (of a GLOF) would be much lower, primarily because the size of the lake would then be substantially smaller and a long, flat glacier tongue would significantly weaken the energy of a possible rock or glacier retreat" (lines 225 - 228).

Despite the strong evidence for the causal link between the CO₂ emissions of RWE and the endangerment of the plaintiff's property the authors however find that "at the current state of science an assessment of GLOF hazard attribution to anthropogenic climate change can only be qualitative." (lines 224f) and "...the company's (= RWE) contribution to Palcacocha GLOF risk is proportionally small and hardly quantifiable." (lines 475 f).

The study by Huggel (et al.) thus doubts the quantifiability of the causal contribution of CO₂-emissions from RWE to the endangerment of the plaintiff's property. This assessment has possibly two reasons:

The authors of the study also include socio-economic factors as risk factors in their analysis, which in fact can hardly be quantified. These socio-economic aspects are however legally irrelevant to the question of whether a scientifically verifiable causal relationship exists between the emission of CO₂ by certain emitters and the risk of a GLOF. Possible failure of local government agencies to prevent damage does not rule out the primary responsibility of those causing the risk. Similarly, a deliberate acceptance of the risk of a GLOF by parts of the population would not preclude such liability of the causers of the risk, but would at most be of relevance in reducing their liability under the aspect of contributory negligence.

The second reason for the cautious conclusion of the authors of the study with respect to the quantifiability of the causal contribution of CO₂-emissions by big emitters to the GLOF-risk endangering Huaraz is probably to be seen in the fact that there are not yet available detailed studies about the regional impacts of climate change in the Andes.

The problem regarding the possible regionalization of the impacts of climate change in the Cordillera Blanca does not, however, exclude the possibility that, even on the basis of current knowledge, a certain range of the size of the causal contribution of climate change to glacial melting in the area of Huaraz can be established.

If it is correct that RWE's CO₂ emissions contribute in the magnitude of X percent to global warming, - according to the IPCC, the melting of the glaciers in the Andes is very likely to be due to climate change or, according to another study, at least two thirds of the loss of mass of the glacier in the Andes can be explained by global warming, - the rise in temperature in the region where the Palcacocha glacier is located is due to global warming as observed in the recent decades, - the increase in the water volume of the lake is almost 100% due to the melting of the Palcacocha glacier due to global warming,

- the GLOF risk for Huaraz is due to the increased water volume of Lake Palcacocha, then the causal contribution of RWE emissions to the GLOF risk lies between (at most) X percent (RWE's share in the increased pollution of the atmosphere with greenhouse gases) and a percentage of (at least) Y percent taking the remaining uncertainties with respect to the regionalization of global warming to the area of the Cordillera Blanca into account. Example: Assuming that possibly only two thirds of the mass loss of the Palcacocha Glacier can be traced with certainty to global warming because of still existing uncertainties with respect to regional effects of climate warming in the Andes Y (the causal contribution of CO₂ emissions by RWE) would be $\frac{2}{3} X$.

This means: Even if it is not yet possible, according to the current state of knowledge, to precisely quantify the causal contribution of individual major emitters of CO₂ to certain consequences of climate change, it does seem possible to determine a range within which this causal contribution must lie and thereby determine the minimum of the respective causal contribution to a certain impact of climate change.

C) Legal aspects

Even a "proportionally small" contribution to the GLOF-risk in question is not legally insignificant in view of the magnitude of the damage threatened by the GLOF.

The lawsuit filed against RWE is based on German law. As in other legal systems, the principle applies that the plaintiff must prove the facts on which his claim is based.

However, this principle does not apply unconditionally. In the case of damage being caused by multiple parties - as in the case of climate change being caused by a large number of actors - the court can estimate the causal contribution of individual parties.

Thus, even if the causal contribution of CO₂ emissions from RWE power plants cannot (yet) be exactly quantified in view of factors that may play a role in the causal chain it can – as the study of Huggel (et al.) confirms – be quantified to a degree that allows a reasonable estimation on which a judicial verdict on the responsibility of individual big CO₂ emitters can be based.

Author response:

We much appreciate this careful analysis provided by Will Frank. We also appreciate the transparency he provides in being involved in the RWE vs Saul Lliuya case. Accordingly, his analysis departs from ours

and offers a different perspective. Our intention is not to analyze issues specifically pertinent to the ongoing legal case, and hence our objective is not to perform an analysis of causality. Rather, our focus is on a comprehensive approach to analyze how multiple drivers of risk, dynamically and over time combine to result in the risk people of Huaraz currently face vis-à-vis a GLOF from Palcacocha. We connect this analysis with the discussion of different associated responsibilities, but again, do not intend to go into any legal responsibility or liability issues. To make the purpose and context of our study clearer we add a specification in the Introduction section (lines 99-100).

We agree that a causal contribution indicating a range is feasible.

In our revision we furthermore address the text section in section 7, lines 585-589, about the contribution of RWE to GLOF risk at Palcacocha and Huaraz. While we think that the basic content of the statement holds valid we recognize that some precision in wording is needed. As addressed in response to the comment below we can distinguish between GLOF hazard and risk, and related attribution, and the ability to quantify contributions by GHG emitters. In the revised version we refer to the potential (and limitations) of quantifying the contribution of global GHG emitters, possibly also indicating a range of contribution. However, we continue to put this in a context of broader risk responsibilities.

Response to short comment by Rupert Stuart-Smith, Fredi Otto, Sihan Li, Gerard Roe

Summary

The submitted manuscript aims to evaluate the physical and socioeconomic drivers of glacial lake outburst flood (GLOF) risk from Lake Palcacocha, a moraine-dammed proglacial lake in the Peruvian Andes. Based on a review of climate science and glaciology literature, the paper finds that ‘the growth of lake Palcacocha has a clear anthropogenic signal’ and that this has significantly increased the GLOF hazard. The paper also considers socio-economic, institutional, governance-related, cultural and emotional drivers of GLOF risk, and the resultant implications for greenhouse gas emitters’ responsibility for compensatory payments in ongoing legal proceedings.

Our comments relate to the accuracy of (1) the authors’ assessment of the attribution of GLOF risk to anthropogenic greenhouse gas emissions, and (2) the framework developed for understanding the drivers of GLOF risk in a legal context.

1. Accuracy of the GLOF hazard attribution

The authors note that (lines 191-203):

‘The only available quantitative glacier attribution study that also includes the tropical Andes concludes that globally more than two thirds of the 1991-2010 glacier mass loss is due to anthropogenic forcing, and for tropical regions finds that an anthropogenic signal in observed glacier mass loss of recent decades is detectable with high confidence (Marzeion et al., 2014). The anthropogenic signal is much stronger for the past 2-3 decades as compared to earlier time periods. Lake growth was highest in the

1990s and 2000s (Fig. 3), coinciding with the period where glacier shrinkage can regionally be attributed to anthropogenic emissions with high confidence. We therefore conclude that growth of lake Palcacocha has a clear anthropogenic signal.’

We are concerned that this statement underestimates the role of human influence on the GLOF hazard from Lake Palcacocha. Regional warming of 0.75-1.5 °C has been attributed to anthropogenic influence (Allen et al., 2018, see fig. 1.3) and mountain glacier lengths act as lowpass filters of the

climate they experience (Oerlemans, 2000; Roe, Baker and Herla, 2017) with multidecadal response times (Jóhannesson, Raymond and Waddington, 1989). This suggests that the expansion of Lake Palcacocha (and the resultant increase in GLOF hazard) is likely to have been attributable to human influence considerably prior to the period over which the authors indicate the presence of an anthropogenic signal.

Further to this, we are concerned the submitted manuscript misinterprets the findings of Marzeion et al., (2014). Taken at face value, the Marzeion et al. calculations would indicate that for low-latitude glaciers (shown in their supplementary material) anthropogenic influence on mass balance emerges only in the last three decades. However, (a) there would be a time lag of at least a decade between the emergence of human influence on mass balance and human influence on glacier lengths (Jóhannesson, Raymond and Waddington, 1989), (b) the glacier's length response to changes in mass balance is strongly influenced by the glacier topography and is therefore specific to the landscape on which the glacier lies, and (c) the results of Marzeion et al. (2014), if taken at face value, would indicate that mass balance was strongly negative throughout the 20th Century. Therefore, if they were an accurate representation of Palcaraju glacier's mass balance, significant glacial retreat would be expected throughout the historical period, rather than only emerging in recent decades as has been observed (as described by the Huggel et al. manuscript). Consequently, the concurrence between the period of time for which mass loss is most attributable to anthropogenic greenhouse gas emissions (according to Marzeion et al., 2014) and the period of most rapid expansion of Lake Palcacocha does not appear to be a solid foundation on which to make a statement of the role of human influence on the observed retreat of this glacier.

With respect to the effect of Lake Palcacocha's expansion on the GLOF hazard, the authors explain that (lines 210-213):

"Some of the factors [influencing GLOF magnitude and probability] (such as lake formation) are closely related to climate change while others can be associated to geologic or geotechnical conditions (e.g. dam stability), or are explicitly influenced by human intervention aiming at reducing the risk of GLOFs (e.g. lake freeboard determined by the height of the constructed drainage canal)."

Anthropogenically-driven glacial retreat has directly resulted in the formation of a large proglacial lake and is the primary and necessary cause of GLOF risk. Non-climatic factors mediate the impact of climate change on the GLOF hazard, but in our view the authors should state explicitly that these factors are less important causes of the present GLOF hazard. The need to implement adaptive measures to reduce GLOF risk is therefore the result of the expansion of Lake Palcacocha and the other factors identified by the authors are largely incidental and would have been inconsequential but for the impact of climate change on the glacier's retreat.

2. Accuracy of the framework for understanding risk, and its relevance for ongoing legal proceedings

The paper gives comparable weight to the physical and 'interacting socio-economic, institutional and cultural processes' which contribute to flood risk. The existence of these social influences on flood risk is not challenged here but this framing obscures the fact that present GLOF risk is a direct result of the anthropogenically-driven retreat of the glacier.

Huggel et al present 'risk (and associated loss and damage) [as] a multi-faceted construction' and argue that 'the question of causality can often not be fully solved, at least not in a quantitative way' and 'in contrast [to the physical GLOF risk causal chain] the current conditions of exposure and vulnerability of people and values in Huaraz to GLOF hazard can only be understood with a historical perspective of social, economic, political and cultural dynamics'. It is undoubtedly true that exposure and vulnerability play a crucial role in determining the ultimate risk, however, non-climatic factors, such as the decision of Spanish colonialists to select this location for the city of Huaraz in the 16th

Century (etc) would not have mattered if not for climate change and thus are, in our view, legally irrelevant as far as the question of causality is concerned. Similarly, we believe that the possible failure of local government agencies to develop successful risk-reduction mechanisms is not relevant for understanding the primary cause of the present GLOF hazard and therefore need to implement costly adaptation measures. Climate change is a necessary cause of flood risk in this setting.

References

Allen, M. R. et al. (2018) 'Framing and Context', in Masson-Delmotte, V. et al. (eds) Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, pp. 49–91.

Jóhannesson, T., Raymond, C. and Waddington, E. (1989) 'Time-Scale for Adjustment of Glaciers to Changes in Mass Balance', *Journal of Glaciology*, 35(121), pp. 355–369. doi: 10.3189/S002214300000928X.

Marzeion, B. et al. (2014) 'Attribution of global glacier mass loss to anthropogenic and natural causes', *Science*. American Association for the Advancement of Science (AAAS), 345(6199), pp. 919–921. doi: 10.1126/science.1254702.

Oerlemans, J. (2000) 'Holocene glacier fluctuations: is the current rate of retreat exceptional?', *Annals of Glaciology*, 31, pp. 39–44. doi: 10.3189/172756400781820246.

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Author response:

We would like to thank the author team of this comment for their engagement with this study and the very valuable comments they provide.

To some extent similar as in the case of the comment by Will Frank we think that we're departing from somewhat different perspectives. In our paper we are primarily interested in how risk evolves over time and what the driving forces are from local to global, and what this means in terms of responsibilities. In this comment there is a stronger push towards the causality issue, which is also important, and we do touch upon it to some extent as well in our paper, but not as a central aspect. Having said this, we're nevertheless glad that you bring up the issue of glacier (and glacier lake) attribution to anthropogenic climate change. Unfortunately, we're confronted with a scarcity of research on climate-glacier attribution in general, and in particular for the tropical Andes region, by far the largest glacierized region in the tropics. We built our attribution analysis (section 3) on existing literature from climatic change in the region to climate-glacier studies. We also agree that we should be more careful in referring to the Marzeion et al. (2014) paper and we clearly acknowledge the problems you outline. We may add to this that one of the underlying problems of this study (and others as well) is the inadequate climate data that is used, with insufficient quality, or temporal and spatial coverage/resolution, a limitation that many climate datasets for this region share due to scarce climatological on the ground measurements and complex topography and climatology in the high Andes. While we don't see the space and scope in our paper to go into substantial detail about climate-glacier change attribution, we revised section 3 to accommodate the concerns that are pointed out here. Specifically, we are happy to take on board the new evidence available from Stuart-Smith et al. (in review).

Based on this comment and the previous one by Will Frank, we revised the following text sections: lines 211-216 and 243-246 (putting the Marzeion et al. 2014 study in perspective, with more evidence by

Stuart-Smith et al. in review); lines 271-278: we revised the statement that GLOF hazard attribution to anthropogenic climate change can only be qualitative and refer here to the Stuart-Smith et al study.

Reference:

Stuart-Smith, R.F., Roe, G.H., Li, S., Allen, M.R., 2020. Anthropogenic contribution to the retreat of Palcaraju glacier (Cordillera Blanca, Peru) and glacial lake outburst flood risk. Nat. Geosci. in review

Furthermore, based on the comments by Will Frank and Stuart-Smith et al. we also recognize the need for further clarification of the type of responsibilities we're addressing in our study. We do not focus on any legal responsibility. We added a clarification at the beginning of section 7 (Implications for responsibility and justice) where we first outline the four aspects when assigning responsibilities. We specifically add that this conceptualization of responsibility encompasses aspects of legal liability, explaining the link between the subject of responsibility and the object of responsibility, but clarify that our understanding of responsibility goes beyond the legal and liability framing. This also addresses the concerns of the two comments that the social, economic and institutional drivers of risk are irrelevant for the court case or decision. We basically agree on this (but the court decision will give us more precision in this respect) but for our concept of responsibility these risk drivers are clearly relevant.

Anthropogenic climate change and glacier lake outburst flood risk: local and global drivers and responsibilities for the case of Lake Palcacocha, Peru

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Abstract. Evidence of observed negative impacts on natural and human systems from anthropogenic climate change is increasing. However, human systems in particular are dynamic and influenced by multiple drivers, and hence identifying an anthropogenic climate signal is challenging.

15 Here we analyze the case of lake Palcacocha in the Andes of Peru which offers a representative model for other glacier lakes and related risks around the world because it features a dynamic evolution of flood risk driven by physical and socio-economic factors and processes. Furthermore, it is the object of a prominent climate litigation case where a local Peruvian citizen sued a large German energy producer over risk of flooding from lake Palcacocha.

20 Adopting a conceptual model of cascading impacts and multiple drivers of risk we first study climatic and other geophysical drivers of flood risk. We find that an anthropogenic signal ~~from flood risk to~~ greenhouse gas emissions is traceable. In parallel, flood risk has been strongly shaped (and increased) by interacting socio-economic, institutional and cultural processes over the past decades.

The case raises important questions ~~about the differentiation of responsibilities~~ for flood risk of global and local agents which, however, are difficult to address in cases like Palcacocha where we reveal a complex network of interlinked global, national and local drivers. Following from this we ~~outline~~ a normative framework with a differentiated perspective on responsibility, implying that global emitters commit to support strengthening capacities in affected regions and localities, and local institutions and societies engage in local risk reduction measures and policies ~~in collaboration with and driven by local communities~~.

1 Introduction

30 Impacts of climate change are increasingly observed in many natural and human systems worldwide (Cramer et al., 2014; Hoegh - Guldberg et al., 2018). Shrinking glaciers are among the most visible indicators of climate change as the mountain cryosphere is especially prone to warming (Dussaillant et al., 2019; Hock and et al., 2019; Zemp et al., 2015). While glaciers

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are widely monitored from the ground and from space, the impacts of glacier changes on natural and human systems are often more difficult to observe, and attribution of the observed changes to causal factors can be challenging (Carey et al., 2017; Hansen and Stone, 2016; Huggel et al., 2016). Changes in water resources and natural hazards are thereby the most substantial effects, and have been documented in many mountain regions of the world (Casassa et al., 2009; Cramer et al., 2014; Harrison et al., 2018). Glacier lake outburst floods (GLOF) are among the most destructive and far-reaching hazards related to glacier changes and have killed thousands of people in single events (Carey, 2005; Carrivick and Tweed, 2016).

Glaciers will continue to shrink and impact downstream natural and human systems in the coming decades, although emission pathways will have a crucial effect on the extent of the process and impacts (Hock and et al., 2019; Huss and Hock, 2018; Kraaijenbrink et al., 2017; Schauwecker et al., 2017). Adaptation to cryosphere impacts is of fundamental importance and has taken place so far in the majority of countries (McDowell et al., 2019). Recent research has emphasized the importance of comprehensively understanding adaptation around socio-cryospheric and socio-hydrologic systems, with accumulating evidence from the Himalayas (Mukherji et al., 2019), including Ladakh (Nüsser et al., 2019; Nüsser and Baghel, 2016) and Tsho Rolpa, Nepal (Sherry et al., 2018), the Andes (Carey et al., 2014) and comparative analyses (Orlove et al., 2019). Some of this research has pointed to adaptation to cryosphere change potentially reaching certain limits, e.g. with the disappearance of glaciers in regions highly dependent on glacier melt water, or large slope instabilities making certain areas uninhabitable or existing livelihood strategies unviable, thus resulting in losses and damages (Huggel et al., 2019). Loss and Damage (L&D) as a concept in global climate policy has been defined as the impacts that cannot or have not been avoided through mitigation and adaptation (Okereke et al., 2014; Warner and van der Geest, 2013), but there is still missing clarity and debate about what L&D comprises (Calliari, 2018; Lees, 2017; Mechler et al., 2019). In the Paris Agreement L&D was anchored in a separate article, but at the same time the agreement specifies that this article does not provide any basis for liability and compensation. Despite this disclaimer at the level of international policy, important questions of responsibility and justice emerge from negative effects and risks related to climate change in general and to the mountain cryosphere specifically, such as: which natural and social processes can be identified as drivers of risk; to what extent are global greenhouse gas emitters contributing to these risks; who must be held accountable to reduce local loss of lives and goods; and under what circumstances are local people, institutions and governments able to manage these risks? There is currently only limited research that offers evidence for and responses to these questions. In this paper, we analyze these aspects from different disciplinary perspectives and associate them with a normative responsibility framework to identify responsibilities for action.

This paper focuses on the glacier lake Palcacocha and associated flood risk for the downstream city of Huaraz in the Peruvian Andes (Fig. 1) to help answer these questions in a specific context and to offer larger insights into climate change risks and responsibilities. While being attentive to a diversity of risk frameworks and concepts (Blaikie et al., 1994; Oliver-Smith, 2013; Wisner et al., 2004), we understand risk as a function of physical hazard, human exposure, and vulnerability of people and assets (IPCC, 2014). Lake Palcacocha offers a representative case for other glacier lakes and related risks around the world because it features many physical and social dynamics found elsewhere: a shrinking glacier that led to the formation of a large glacier lake where ice previously existed; continued lake instability due to glacier retreat and moraine dam instability; a past glacier lake outburst flood that killed thousands of local residents and partially destroyed a city and other communities and

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80 infrastructure; repeated flood prevention and lake drainage engineering works; a history of glacier lake monitoring and ongoing
scientific studies; contested knowledge, science and perceptions about the lake and its risks among experts, policymakers,
local residents, and other groups; a complex political and institutional context with periods of increased attention and neglect
of the problem by authorities and the local population; unclear responsibilities among different government agencies and
levels; and, overall, a dynamic evolution of risk driven by physical and socio-economic factors and processes. Our objective
85 is to analyze to what extent we can identify natural and social processes as factors and drivers of risk at lake Palcacocha and
in Huaraz, and discuss whether this analysis can inform the conceptualization of responsibilities related to managing the
negative impacts of anthropogenic climate change.

This analysis is timely not only because glacierized mountain regions are increasingly grappling with unstable glacier lakes,
but also because Lake Palcacocha recently made headlines worldwide because of a legal case, Saúl Luciano Lliuya vs RWE
90 (Frank et al., 2019). This case, pending at a German court,¹ emerged when a local resident of Huaraz (Luciano Lliuya), sued
the German energy producer RWE over flood risk from glacier lake Palcacocha, threatening his property if the lake were to
cause a flood. Luciano Lliuya argues that Palcacocha is unstable as a result of anthropogenic emissions (to which, he alleges,
RWE made a significant contribution), which caused glacier retreat and the growth of lake Palcacocha, making the lake
unstable and threatening downstream communities. The case was initially dismissed at a local German court but then admitted
95 by a higher appeals court. As the first lawsuit of its kind to reach this stage, it was considered a significant breakthrough in
climate litigation (Ganguly et al., 2018; Huggel et al., 2016). Although the literature on climate litigation is steadily growing
(Marjanac and Patton, 2018; McCormick et al., 2018), questions of responsibility, and possibly liability, in a case like
Palcacocha, remain mostly unanswered and hence call for studies that analyze risk and responsibility during climatic,
cryospheric, and societal change. The purpose of this paper, however, is not to analyze legally relevant questions of causality
100 but rather substantiating and situating the Palcacocha case in a broader context and concepts of responsibilities.

To achieve a comprehensive picture of flood risk in Huaraz and the relation to climate and socio-economic change we make
use of existing data and information, and conduct additional research where needed, including hazard field studies, numerical
flood modeling, satellite data analysis, census data and interviews. We structure our paper as follows: we first analyze the
105 physical evolution of lake Palcacocha from the mid-nineteenth century Little Ice Age (LIA) to the present (section 2). We then
disentangle the different drivers of GLOF risks following the aforementioned IPCC-based risk concept. We begin with the
physical hazard component of risk, studying how global drivers of anthropogenic greenhouse gas emissions affect the local
conditions of GLOF hazard (section 3). We collected remote sensing and fieldwork-based information to document the
evolution of lake Palcacocha. We analyzed the hazard conditions at and around the lake to develop a number of flood scenarios
110 that we then implemented in a physically based GLOF flow model following established methodologies to evaluate the
downstream hazard in Huaraz. We then look at how social, economic, institutional, and cultural aspects become drivers of risk
exposure and vulnerability (sections 4-6). For this purpose, we used a mixed methods approach to elucidate various
environmental and socio-cultural drivers that contribute to risk. Our historical analysis of risk development in Huaraz derives
primarily from historical document analysis, literature review and interviews with contemporaneous figures. The more recent

¹ Saúl Ananías Luciano Lliuya ./ RWE AG, Oberlandesgericht Hamm, Az.: I-5 U 15/17

115 analysis of socio-cultural and institutional factors contributing to risk (since 2009) draws on qualitative data from participant
observation in institutional, urban and rural settings as well as interviews with people from these three spaces.
This case demonstrates the inherent links between local and global activities to manage climate risks, and how they drive
localized climate-related risks. The local-global linkages raise many questions about causality, liability, responsibility and
justice (section 7). Our assumption is that a better understanding of the diverse drivers of risk in a case like Palcacocha allows
120 us to clarify the differentiation of responsibilities and the challenges ahead vis-à-vis impacts and risks of loss and damage.

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2 Lake Palcacocha

The evolution and history of Lake Palcacocha in Peru's Cordillera Blanca is linked to glacier retreat, driven by both natural
and anthropogenic forcing, large flood disasters as well as human intervention and flood mitigation at the lake (see Tab. 1).
According to the lichenometric dating, the moraine which later dammed the lake developed between 1590 and 1630 (Emmer,
2017) by advancing glaciers from the southwestern slopes of Palcaraju (6,274 m a.s.l.) and Pucaranra (6,156 m a.s.l.)
125 mountains. This period corresponds to the beginning of the first, more distinct phase of the LIA in the Cordillera Blanca
(Thompson et al., 2000; Solomina et al., 2007). It is not known precisely when the lake formed; however, based on the available
evidence we estimate that it was likely after the second phase of the LIA in the second half of 19th Century. The Palcacocha
drainage outlet nourishes the Paria river, joins other waterways downvalley and flows into the Quillcay River that runs through
130 downtown Huaraz, the capital city of Peru's Ancash Region with approximately 140,000 inhabitants today.

The first scientific expeditions and observations of the lake were undertaken by Austrian and German researchers, led by Hans
Kinzl in the late 1930s, a time before anyone realized the threat that Palcacocha posed to downstream communities (Carey,
2012; Portocarrero, 2014; Wegner, 2014). Shortly after, on 13 December 1941, Lake Palcacocha's moraine dam failed,
resulting in a GLOF with a volume of > 10 million m³ and peak discharge in excess of 10,000 m³/s, producing devastating
135 impacts in the city of Huaraz, located ca. 25 km downstream from the lake (Mergili et al., 2020; Somos-Valenzuela et al.,
2016). The flood killed nearly 2000 people and destroyed one-third of the city of Huaraz, particularly its most developed
downtown area and modern commercial district (Carey, 2010; Wegner, 2014). This event is considered among the worst floods
ever documented worldwide resulting from natural dam failure (Carrivick and Tweed, 2016; Costa and Schuster, 1988).
Although the precise cause is not known, the 1941 flood likely followed an impact of an ice avalanche into the lake or failure
140 related to piping in the dam (Oppenheim, 1946).

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After the 1941 GLOF, a small 'residual' lake remained, dammed by the basal moraine (elevated part of the former bottom of
the lake basin). The lake volume remained relatively stable for several decades (Figs. 2, 3), even when a heavy earthquake on
31st May 1970 (M=7.9) caused disastrous effects on the region (Liboutry et al., 1977). In the early 1970s, after almost three
decades of minimal lake growth or stagnation, a permanent drainage canal and two artificial dams were constructed, lowering
145 the lake water level by 1 m, and stabilizing it at 4,566 m a.s.l. with 7 m of freeboard and 0.515 · 10⁶ m³ of water (Table 1). The
contemporary period of glacier retreat and downwasting accompanied by lake expansion started by the end of the 1970s and
extends to present (Vilimek et al., 2005).

150 On 19th March 2003, the left lateral moraine along lake Palcacocha slid into the lake and produced a displacement wave that overtopped the dam and caused a small lake outburst flood further downvalley. This flood, combined with an inaccurate but high-publicity NASA announcement one month later in April 2003 about glacier instability above Palcacocha re-opened discussions about the lake's threat to the city of Huaraz (Carey, 2010; Kargel et al., 2011). Given the more than 110,000 inhabitants of Huaraz at the time, these events led to a number of new hazard and risk assessment studies (e.g., [Hegglin and Huggel, 2008](#); [Vilimek et al., 2005](#)). The lake volume at that time was determined as $3.690 \cdot 10^6 \text{ m}^3$ (+640% in 29 years; (Zapata et al., 2004), although some doubts have arisen concerning the accuracy of this 2003 lake bathymetry and the lake area in fact would suggest a higher lake volume. The existing hazard mitigation measures built in the 1970s were no longer found sufficient (Emmer et al., 2018). In 2009, a new bathymetry revealed that the lake had grown to $17.325 \cdot 10^6 \text{ m}^3$ (Portocarrero, 2014). As a response, six siphons were installed in 2011 to temporarily reduce lake volume prior to the implementation of a permanent engineering solution. This project progressed slowly in the context of institutional instability, and volume regulation remains ongoing in 2019 with a set of 10 siphons.

160 With a volume of $17.403 \cdot 10^6 \text{ m}^3$ in 2016 (i.e., +3,380% in 42 years; UGRH, 2016), Lake Palcacocha is among the largest moraine-dammed lakes in the Cordillera Blanca. Further potential for lake growth is, nevertheless, limited by topographic constraints of lateral side moraines and bedrock slope reached in the rear part of the lake. According to the recent lake inventory and GLOF susceptibility assessment (Emmer et al., 2016), Palcacocha is among the lakes susceptible to produce a GLOF, which could be triggered by rapid landslide processes from surrounding moraines, ice and rock slopes. Detailed study of potential landslide-induced outburst flood was performed by (Klimeš et al., 2016) and flood and inundation hazard modelling for Huaraz was published by (Somos-Valenzuela et al., 2016) and (Frey et al., 2018), suggesting a decreasing hazard level if the water level is lowered. The population of Huaraz has increased from approximately 12,000 residents at the time of the 1941 GLOF to about 140,000 today, with tens of thousands inhabiting the path that the 1941 followed along the Quillcay River.

3 Physical drivers of risk

In this section we explore to what extent flood hazard and risk from lake Palcacocha can be attributed to anthropogenic climate change and to other physical drivers of risk. This is a challenging task with hardly any precedence and first needs some conceptual considerations, drawing on recent understandings of how impacts can be attributed to (anthropogenic) climate change (Cramer et al., 2014; Stone et al., 2013). A formal attribution study investigates whether a particular system has shown any observable trend and whether this trend can be attributed to anthropogenic climate change. Figure 4 visualizes a cascade of impacts from anthropogenic emissions to climate change, glacier shrinkage and lake growth, and eventually to GLOFs and resulting flood hazard and damage. If we want to decipher the influence of climate change on GLOF hazard we need to analyze each component of this cascade of impacts, considering that a varying number of confounding factors (i.e. factors not related to climate [change](#)) interact at each stage.

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185 In this cascade, we start with climate change where attribution research has a long and advanced track record and would typically conclude with a statement such as to what degree the observed climatic changes or trends can be attributed to anthropogenic emissions (Bindoff et al., 2013; Stott et al., 2000).

190 Specific studies on the attribution of observed climatic trends in the tropical Andes to anthropogenic emissions hardly exist so far. Global-scale attribution studies and assessments, however, have considered the broader Andes and Pacific coastal region. (Bindoff et al., 2013; Jones et al., 2013) show that temperature changes in this region are broadly in line with climate model runs including anthropogenic forcing and clearly deviate from model runs with natural forcing only. Further research has analyzed the observational temperature and precipitation record of the region over the past decades and the link to phenomena of climatic variability such as the El Niño Southern Oscillation (ENSO) (Heidinger et al., 2018; Vuille et al., 2008). (Schauwecker et al., 2014; Vuille et al., 2015) concur in that temperatures in the Andes of Peru, including the Cordillera Blanca, 195 have increased since the beginning of the observational record in the 1960s at rates of about 0.2 to 0.3°C per decade, with reduced warming rates during the last ca. 30 years (~0.1°C per decade).

While ENSO and the Pacific Decadal Oscillation (PDO) exert an important influence on an interannual or decadal scale, anthropogenic radiative forcing has been identified as the most likely cause of the longer term warming (Vuille et al., 2015). We proceed along the impact cascade (Fig. 4) with glaciers. Glaciers are closely coupled to the climate system, but surprisingly, 200 there exist only very few studies worldwide that explicitly attribute glacier change to anthropogenic climate change. If we revisit glacier decay in the Cordillera Blanca, including the Palcacocha area, we find a phase of rather strong glacier retreat in the late 19th century, followed by a slow-down in the early 20th century with small advances in the 1920s (Kinzi, 1969). Later, a period of strong glacier shrinkage in the 1930s and 1940s led to a phase of slow retreat in the 1950s to 1970s, eventually followed by very marked glacier loss since the late 1970s until present (Georges, 2004; Hastenrath and Ames, 1995; Kaser and Georges, 1997; Rabatel et al., 2013). The continuous mass loss since the late 1970s was enhanced (or reduced) by variations of the Pacific sea surface temperatures, and El Niño and La Niña phases, respectively, with ENSO exerting a significant effect on Andean glaciers on interannual time scales. The long-term glacier shrinking trend, however, cannot be explained by ENSO-related variability (Schauwecker et al., 2014; Vuille et al., 2015), and therefore climate change clearly plays a significant role. This is also reinforced by the IPCC who attributed glacier retreat in the Andes to climate change with very high confidence (Magrin et al., 2014).

210 A global-scale study finds that more than two thirds of the 1991-2010 global glacier mass loss is due to anthropogenic forcing, while for tropical regions (including the Cordillera Blanca) an anthropogenic signal in observed glacier mass loss of recent decades is detectable with high confidence (Marzeion et al., 2014). A new study, however, focusing specifically on Palcaraju glacier (the glacier driving the growth of Lake Palcacocha) concludes that close to 100% of the observed temperature trend of 1.3°C warming since 1880 can be attributed to anthropogenic climate change, and that the glacier's retreat is entirely attributable to the observed temperature trend (Stuart-Smith et al., 2020).

215 We now analyze how Palcacocha lake growth relates to glacier shrinkage and anthropogenic climate change. Lake Palcacocha extends on a relatively flat area that was previously occupied by glacier ice, and is dammed by LIA and early 20th century

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Moved up [1]: that globally more than two thirds of the 1991-2010 glacier mass loss is due to anthropogenic forcing, and for tropical regions finds that an anthropogenic signal in observed glacier mass loss of recent decades is detectable with high confidence (Marzeion et al., 2014).

240 moraines. Lake growth at Palcacocha can therefore be attributed to glacier retreat in a straightforward way as glacier ice was simply replaced by lake water, and close to 100% of the lake growth can be explained by glacier retreat (Fig. 2). Thermal energy of lake water accelerates ice mass loss at the glacier front, generating a positive feedback between glacier retreat and lake growth (Kääb and Haeberli, 2001). Lake growth was strongest in the 1990s and 2000s (Fig. 3), coinciding with the period of high anthropogenic emissions. Considering our well documented glacier retreat and lake growth and new evidence on attribution of Palcaraju glacier's retreat from (Stuart-Smith et al., 2020) we therefore conclude that the growth of lake Palcacocha over the past three decades cannot be explained by natural variability and has a clear and high anthropogenic signal.

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How GLOF hazard and risk in Huaraz or elsewhere can be attributed to anthropogenic climate change is still an open field of scientific debate. Physically, flood risk in Huaraz is determined by GLOF hazard which is a function of the magnitude (or intensity, such as flood height) of a hazardous process at a given location, and its probability of occurrence (Raetzo et al., 2002; UNISDR, 2009). A number of factors influence and determine GLOF magnitude and probability of occurrence at lake Palcacocha, notably lake volume, dam stability and freeboard, and landslides from unstable moraines or ice/rock avalanches impacting the lake (Emmer and Vilímek, 2013; Schneider et al., 2014). Some of the factors (such as lake formation) are closely related to climate change while others can be associated to geologic or geotechnical conditions (e.g. dam stability), or are explicitly influenced by human intervention aiming at reducing the risk of GLOFs (e.g. lake freeboard determined by the height of the constructed drainage canal). In addition to effects on glacier retreat, climate change can influence some of these hazard-determining factors, e.g. increasing temperatures can degrade permafrost and thus destabilize the flanks of the steep headwalls surrounding lake Palcacocha, or alter thermal conditions and stability of steep glaciers (Carey et al., 2012; Faillettaz et al., 2015; Haeberli et al., 2017).

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260 To assess how GLOF hazard at lake Palcacocha translates into flood hazard in the city of Huaraz we draw on numerical mass flow simulations by (Frey et al., 2018) and (Somos-Valenzuela et al., 2016), who modeled different scenarios of avalanches impacting the lake and producing dam overtopping waves and downstream propagating floods (see Suppl. Material). They follow state-of-the-art hazard assessment approaches (GAPHAZ, 2017), which was also applied to others lakes in the Cordillera Blanca (Schneider et al., 2014). Corresponding model results indicate that an urban area of similar size as destroyed by the 1941 GLOF is threatened by high GLOF hazard and thus by potential devastating effects (Fig. 5). Previous studies estimated about 40,000 people living in the inundation zone with a potential death toll of close to 20,000 (Somos-Valenzuela, 2014). Based on spatial census data from the National Statistical Institute of Peru (INED), here we found that about 22,500 inhabitants living in the high hazard zone are highly exposed to GLOF (Fig. 5). However, because the high hazard zone intersects with the central business and market places of Huaraz the number of people present during the day times is much higher, possibly up to 50,000.

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270 While recent studies quantitatively attributed the retreat of Palcaraju glacier to anthropogenic climate change (Stuart-Smith et al., 2020) it remains to be clarified whether quantitative attribution can also be achieved for GLOF hazard encountered at Huaraz or whether only qualitative statements are possible at the current state of science. Overall, and despite of non-climatic factors also influencing GLOF hazards, we can confidently state that the clear and strong signal of anthropogenic emissions in the growth of lake Palcacocha translates to GLOF hazard in Huaraz. In the absence of anthropogenic climate change the flood

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hazard would be much lower, primarily because the size of the lake would be substantially smaller and a longer, flat glacier tongue, as it was the case in 1941, significantly attenuates the impact energy of potential ice or rock/ice avalanches (Mergili et al., 2020).

4 Socio-economic drivers of risks

295 While physical drivers of GLOF hazard such as climate change, ice loss, and glacier lake expansion increased risk in the valley below Lake Palcacocha, many societal drivers of risk have simultaneously intersected with geophysical changes and have exacerbated vulnerability and people's exposure in Huaraz. Socio-economic status, governance and institutional aspects, technology and knowledge production, and cultural forces have all influenced GLOF risk from Palcacocha. For one, risks stem from the placement of the city of Huaraz and its ever-increasing population at the confluence of the lower Quillcay River and the Santa River, where several Cordillera Blanca lake basins drain. Spanish colonists initially founded Huaraz in the sixteenth century, preferring to build their towns on valley floors in riparian zones, a pattern that contrasted with pre-Columbian populations that implemented a form of hazard adaptation by settling in upland areas away from alluvial fans (Oliver-Smith, 1999). The 1941 Palcacocha GLOF illustrated the consequences of this placement and the city's long-term exposure to Cordillera Blanca hazards (Wegner, 2014).

305 Following the flood, authorities attempted to reduce hazard-zone inhabitation by prohibiting construction in the GLOF path, but residents and newcomers ignored the hazard zoning policies and the government did not enforce its mandate (Carey, 2010). After the devastating 1970 earthquake destroyed much of Huaraz, the government again prohibited reconstruction in the 1941 GLOF path due to new concerns about unstable glacier lakes above Huaraz (Bode, 1990; Carey, 2010; Oliver-Smith, 1986). Once again, residents defied government hazard zoning, both rebuilding downtown Huaraz and expanding upstream along the banks of the Quillcay River toward Palcacocha and other glacier lakes. According to flood hazard assessment and mapping presented in Figure 5, the Huaraz inhabitants most exposed to a future Palcacocha GLOF cluster along the Quillcay river in the districts of Nueva Florida, Antonio Raimondi, Centenario, parts of San Francisco, Huarupampa, Nicrupampa, José Olaya and Patay, which have largely expanded in the past decades (Bode, 1990; Carey, 2010; Wegner, 2014). Figure 6 spatially compares the urban area of Huaraz from the immediate aftermath of the 1941 GLOF to the current situation, revealing enormous urban growth including the most hazard-exposed areas. Census data from a similar timeframe also shows an enormous population increase from about 11,000 in 1940 to more than 140,000 in 2017 (Fig. 7). Several reasons motivated inhabitants to resettle and build within the potential path of a Palcacocha GLOF, even though they recognized the GLOF risks. Analysis of these reasons helps illuminate socio-economic drivers of GLOF risk that are useful not only for understanding Palcacocha, but also for evaluating GLOF and hazard risk worldwide.

320 First, inhabitants recognized key economic factors: some believed they would incur direct economic losses if they moved away, while others thought that inhabiting the area along the Quillcay River adjacent to Huaraz would yield economic gains. This dynamic emerged as early as the 1940s, and residents were outspoken about defending their rights to live in the potential GLOF path - often based on economic reasoning - starting in the 1950s (e.g. Anonymus, 1956, 1951, 1945). Inhabitation of flood-prone areas and other places susceptible to natural disasters, even when people understand the risks, is not unusual (e.g.

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Steinberg, 2000; Wisner et al., 2004). In Huaraz, however, many worried that the government would not compensate them for their lost land or provide them with a comparable plot and home elsewhere. Others were concerned that relocation of the city or even moving upslope to safer terrain would diminish Huaraz's position as the region's financial hub, where jobs and markets offered opportunities, transportation and commercial centers attracted people, and banks and credit institutions existed (Doughty, 1999; Oliver-Smith, 1977, 1999). While many were reluctant to leave Huaraz for these economic reasons, others migrated into the city for related motives, such as receiving relief and disaster aid following the catastrophe (Walton, 1974; Wrathall et al., 2014).

One part of Huaraz, the Nueva Florida district adjacent to the Quillcay River, exemplifies these economic incentives outweighing GLOF risks. Ethnographic research we conducted in the area provided insights that exemplify the historical and contemporary factors playing into this dynamic. Quechua-speaking farmers from the highlands above Huaraz began buying inexpensive property in Nueva Florida after the 1970s. This previously vacant land was not only affordable but also offered proximity to employment, public services, and overall a higher standard of living for historically marginalized people. In the 1990s, new multinational mining operations near Huaraz triggered an influx of mine workers who frequently settled in Nueva Florida. Given the district's growth, authorities built paved roads and installed electricity and sewage networks in Nueva Florida in the early 2000s. Today, Nueva Florida is a flourishing district, attracting even more people to the area along the Quillcay River. While authorities have officially prohibited construction in Nueva Florida since Palcacocha GLOF risk concerns arose again in 2009, residents attest that officials tolerate the construction of smaller buildings. Over time, living in Huaraz provided a unique opportunity for Quechua-speaking villagers to access social and economic opportunities in Huaraz. According to a survey we conducted in 2017 (see Suppl. Material), most Nueva Florida residents showed little concern for the risk of flooding, neither in the past nor today. Though many were aware of recent public and media discussions about the threat of a Palcacocha GLOF, they contended that such warnings were exaggerated. It appears that economic and material benefits of inhabiting Nueva Florida outweigh the potential flood risk.

Second, social status among Huaraz residents - influenced primarily by racial and class divisions - has been another key factor influencing GLOF risk and explaining some inhabitants' continued occupation of the Quillcay riparian zone. Cities like Huaraz have long been inhabited by the ruling classes - the Spanish-speaking residents and supposedly non-indigenous people (Oliver-Smith, 1999). Living higher and more rural, on the other hand, signified a poorer, more indigenous status in this culturally-constructed schematic of race-class dynamics (Walton, 1974). Post-disaster urban zoning after the 1941 GLOF and 1970 earthquake that attempted to relocate populations to safer ground higher above the river came to symbolize, for some, a government-imposed assault on ruling class privilege, downward social mobility and loss of socioeconomic status (Bode, 1977, 1990; Carey, 2010; Doughty, 1999).

Analysis of GLOF risks, exposure and vulnerability must consider both how inhabitants rank their risks and how disaster prevention policies such as hazard zoning, building practices, and urban planning affect socio-economic status. It is difficult to pinpoint responsibility for people's decisions to inhabit the potential GLOF path below Palcacocha. Inequality driven by class and race divisions has led to the marginalization of some segments of the Peruvian population. As a result, their decision-making may be shaped by economics, livelihood and employment opportunities, social standing, and other socio-economic factors that are usually impossible to assign to certain individuals but rather to larger forces such as racism, poverty, and global

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inequality. Furthermore, the economic level of Peruvians, including the citizens of Huaraz, is also affected by global histories and legacies of colonialism, neoliberalism, resource extraction, political domination, and economic marginalization. Parts of these historical processes continue to affect the lives of people in Huaraz which contribute to make them, generally speaking, poorer compared to residents of the most developed nations who tend to have lower levels of vulnerability and can afford to rank risks differently than Peruvians living beneath lake Palcacocha (Carey, 2010).

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5 Institutional and governance-related risk drivers

Institutions, policies, and governance also affect levels of GLOF risk. In particular, government instability, fluctuating support (funding and resources), and institutional inconsistency creating confusion about disaster-prevention roles and responsibilities have all exacerbated risk below lake Palcacocha. It initially took ten years after the 1941 Huaraz disaster to form the first GLOF-prevention office, the Control Commission of Cordillera Blanca Lakes (CCLCB). Since establishment of the first glaciology and lake security office in 1951 to mitigate Cordillera Blanca GLOF risks, the agency has passed through four different ministries, had twelve different names, and even disappeared completely for nearly four years in the late 1990s (Carey, 2010). Some disaster events (e.g. 1950 Los Cedros GLOF, 1970 earthquake and Mount Huascarán avalanche) and some authoritarian governments (e.g. Presidents Odría in the 1950s and Velasco in the 1970s) stimulated strong investments in Cordillera Blanca GLOF prevention. At other times, glacier disasters (1962 Ranrahirca avalanche) and authoritarian governments (President Fujimori in the 1990s) triggered little government response or even backward steps in GLOF risk reduction.

Decentralization of the national government has also exacerbated institutional inconsistency and instability, which also influences GLOF risk. Prior to the 2002 start of the decentralization process, Peru's 25 departmental governments functioned as administrative extensions of the national government, with departmental governors (prefects) appointed by the national government. During this period, the central government directed and consolidated Cordillera Blanca GLOF monitoring and mitigation. Decentralization created new, more autonomous regional governments that were elected (Arce, 2008; Dickovick, 2011). On paper, the reforms made the Ancash Regional Government primarily responsible for identifying and implementing Palcacocha risk reduction measures. But in practice, decentralization generated confusion about jurisdiction, expertise, authority, funding, and responsibility, often leading to stagnation and non-action that left residents more vulnerable or exposed to potential GLOFs.

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Amidst decentralization, the Ancash government has also experienced exceptional turmoil in recent years: since 2014, three governors of Ancash have been imprisoned over charges including corruption and assassination (El Comercio, 2018). Further, there remains a host of national government institutions and ministries with jurisdiction over the Cordillera Blanca, including the Glacier and Lake Evaluation Office (formerly Glaciology and Water Resources Unit, UGRH) of the National Water Authority (ANA) and associated local and provincial water authorities, and Huascarán National Park. They interact with the Ancash Regional Government, provincial and municipal authorities and their corresponding entities such as civil defense, rural community jurisdictions (*comunidades campesinas*), and a host of other stakeholders including mining companies, Duke Energy, and non-governmental organizations (NGOs). More specifically for GLOF risk reduction, the national government

410 agencies ANA, and the National Institute for Glacier and Mountain Ecosystem Research (INAIGEM), founded in 2015, operate in the Cordillera Blanca but sometimes overlap in confusing ways, ultimately impeding institutional capacity to respond to increasing glacier risks.

415 This regional government instability and uneven decentralization has obstructed effective GLOF risk reduction measures at lake Palcacocha specifically. In 2003, Palcacocha overflowed and caused a small flood due to a landslide into the lake (Vilimek et al., 2005). While debate ensued about jurisdiction and responsibility (e.g. Congreso de la República, 2003), it took nearly a year to conduct a bathymetry study and repair the damaged flood protection dam at the lake. In 2009, when a new study revealed that Palcacocha contained 17 million m³ of water (more than it had for the 1941 GLOF), no single institution took charge to lead a permanent engineering project to partially drain and secure the lake, as the UGRH had done for decades in the past. Instead, the institutional instability generated only short-term, unsustainable measures (temporary siphons) to protect downstream populations, despite repeated studies documenting Palcacocha risks (Hegglin and Huggel, 2008; Klimeš et al., 2016; Portocarrero, 2014; Somos-Valenzuela et al., 2016; Vilimek et al., 2005).

420 In response to political inaction at a regional level, the local governments of Huaraz and Independencia – the two main municipalities affected by GLOF risk from Palcacocha – have collaborated to implement a Palcacocha early warning system. Moreover, in 2016, international experts in cooperation with local institutions released a new hazard map, including GLOF hazards and evacuation plans, for the Quillcay catchment (Frey et al., 2018), cf. Section 3 above). International scientific institutions and NGOs took primary charge of producing the map, in collaboration with, but without leadership of local, regional, or national institutions in Peru. Overall, combined effects have contributed to the increase of risk, namely related to decentralization of the national government, institutional instability, conflicting roles and jurisdictions, and waning government support for Palcacocha hazard reduction research, monitoring, and projects. Given the complexities surrounding these processes and dynamics over time a more detailed indication of their contribution to risk is elusive.

6 Cultural and emotional components of risk

Cultural factors also influence risk in the valleys below lake Palcacocha. Attachment to place can motivate people to inhabit potential flood zones, while varying local explanations of cause-effect (particularly causation between human behavior and environmental change) can also yield certain understandings of risk that collide with scientific assessments and may lead to inaction in the face of GLOF risks. Research on these cultural dimensions of glaciers is growing, elsewhere (Allison, 2015; Cruikshank, 2005; Sherpa, 2014; Sherry et al., 2018), and in the Peruvian Andes and Cordillera Blanca, where locals often perceive sentient landscapes and maintain spiritual relationships with mountains and glaciers (Bolin, 2009; Carey, 2010; De la Cadena, 2015; Jurt et al., 2015). One key cultural driver of risk along the Quillcay River is the emotional and psychological attachment to place that has historically attracted people to Huaraz, even after the 1941 GLOF and 1970 earthquake devastated the city. A profound sense of place – that is, attachment to homelands, personal identity, heritage, familiarity with landmarks and landscapes, and links to community – frequently bonds people to particular places, not just in areas prone to GLOFs but in disaster zones worldwide (Hastrup, 2013; Oliver-Smith, 1982; Sherry et al., 2018). These attachments to land and community also motivated people to remain living in Huaraz, even after disasters struck or when they had knowledge of GLOF risks

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445 (Bode, 1990; Oliver-Smith, 1982, 1986; Yauri Montero, 1972). While some survivors emigrated to Lima after the 1941 and 1970 disasters, others remained in their former homeland, connected to their birthplace, close to those who died in the disasters, and part of the same community where they had always lived and experienced trauma.

Another factor influencing risk is the diverse understandings of environmental processes and hazards, particularly where scientific and technical explanations contrast with local beliefs and values. In May 2017, two ice avalanches descended into lake Palcacocha within a 24-hour period, causing three-meter high waves that lake workers witnessed. The workers' supervisor maintained that this event occurred because he had not paid tribute to Palcacocha and the surrounding mountains. For workers at Palcacocha and other Quechua-speaking farmers living nearby, the lake and mountains are beings that require respectful engagement. According to this understanding of glaciers and lakes, spiritual disruptions could trigger a GLOF – such as lake workers' inadequate offerings to mountain beings, rather than only geophysical processes such as glacier and bedrock instability. Some local accounts voiced that past glacier-related disasters such as the 1941 GLOF occurred because people failed to show the landscape entities adequate respect (Yauri Montero, 2000). According to our interviews and focus groups we conducted in 2017 and 2018, some elderly villagers in areas below Palcacocha corroborate these stories. In one of these local's accounts of the 1941 flood,² a deity told a rural woman to perform a ritual offering at Palcacocha. When she failed to do so, the lake became angry and flooded Huaraz. Asked why Cordillera Blanca glaciers are melting, lake workers at Palcacocha pointed to contamination and global industry. While they recognized a global dimension of environmental change, they regularly paid tribute to the lake and mountains in an effort to prevent disaster. As long as the supervisor kept the lake happy with offerings of coca leaves and alcohol, he explained, there would be no GLOF disaster.

These accounts thus reveal how local people perceive both global and local aspects as drivers of risk, but their perceptions are often not in line with technical and scientific assessments of risk. For instance, many urban and rural residents have referred to enchanted lakes, which, in local understandings, can lure people to their shores and then suck people inside, to the other world, if they do not perform proper rituals or resist approaching these lakes (Carey, 2010; Yauri Montero, 2000). Other residents offer different cultural explanations for natural disasters, such as Catholic residents saying that the 1970 earthquake resulted from sinners' behavior and God's will (Bode, 1990; Oliver-Smith, 1986). Attributing GLOFs to their neighbors' behaviors or to the will of certain deities can ultimately lead to a relinquishment of responsibility and fatalism: why move outside a potential GLOF path if floods are determined by God's will or neighbors' sins? When a resident believes sinning causes floods or coca leaf offerings presented to mountain deities stabilize glacier lakes – as opposed to the scientific conclusions attributing these processes to climate change, glacier shrinkage, or bedrock geometry – then development and implementation of risk reduction plans become more difficult, because not everyone agrees about the source of the hazard. In fact, people in Huaraz negotiate cultural and scientific understandings of flood risk on a daily basis, and may regard multiple explanations as valid.

These trends in the Cordillera Blanca also exist internationally, and people knowingly inhabit areas exposed to GLOFs in other glacier-fed watersheds. In some cases, they are "forced" into these areas due to cheaper land in the floodplain or nearby job and livelihood opportunities (Carey et al., 2014; Orlove et al., 2019). In other cases, they select GLOF-prone sites to live due to historical and cultural connections to those flood-prone places (Sherry et al., 2018), or they utilize other cultural or spiritual

² Interview conducted in 2017

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485 techniques to manage glacier-related risks (Allison, 2015; Gagné, 2019), or they possess different local knowledge about risk that sometimes differs from scientific or institutional assessments of GLOF risks (Drew, 2012; Williams and Golovnev, 2015). Furthermore, in India for example, there are also documented recent major GLOF disasters due to exposure and high vulnerability of a large number of people due to religious and tourism related reasons (Allen et al., 2016).

7 Implications for responsibility and justice

490 So far we have examined physical climate change related, socio-economic, institutional and cultural aspects of Palcacocha GLOF risk. Drawing on that, we now analyze the possible implications for responsibility, and ask how concepts of justice can inform these and other similar issues. Responsibility as a concept commonly concerns four aspects that become relevant when analyzing the differentiation and assignment of responsibilities in specific circumstances and at different policy levels (Bayertz, 1995): i) Someone (the agent or subject of responsibility) is responsible for ii) something (the object of responsibility) and answerable to some iii) institution according to some iv) norm. This conceptualization of responsibility encompasses aspects of legal liability or causal responsibility, explaining the link between the subject of responsibility and the object of responsibility that becomes relevant in legal cases like the court case Lliuya vs RWE. However, this understanding of responsibility is more general including aspects and concerns leading beyond a more narrow legal understanding of responsibility in the sense of liability.

495 Responsibility in this wider understanding often concerns different agents and objects (Wallimann-Helmer, 2016). In the case of Palcacocha, a complex network of responsibilities and dependencies exists between different agents of responsibility and institutions. Differentiation and assignment of responsibilities to subjects depends on the perspective of the different drivers of GLOF risk, and on whether a forward- or backward-looking concept of responsibility is adopted (Miller 2007). Backward-looking assignment of responsibilities identifies the agents bearing responsibility for risks and outcomes already materializing and can be adopted to justify corrective duties. Forward-looking ascription of responsibilities concerns remedial duties to prevent negative impacts or minimizing risks (Burns and Osofsky, 2009; Grossman, 2003).

500 Observed physical risk drivers indicate that to a large extent glacier shrinkage and lake growth are due to anthropogenic climate change that contribute to GLOF risks. Detection and attribution research is primarily a backward-looking science and may inform the assignment of responsibilities for past emissions causing present climate risks (Huggel et al., 2016; James et al., 2019). Historically, emitters contributing to climate change are primarily highly developed western countries and regions, with large emerging economies strongly increasing their emission footprint over the past couple of decades. Accordingly, detected and attributed physical risk drivers of GLOFs allow us to ascribe some responsibilities for increased risk of GLOFs to these countries and regions. In climate litigation, countries or private companies, typically large corporations as in the case of Lliuya vs RWE, are sued by plaintiffs, and courts verify the legal responsibilities (liabilities) of these entities.

505 Attribution research has only limited explanatory value for assigning forward-looking responsibilities, which also depends on the extent to which specific future risks are controlled by past emissions and related environmental changes. For instance, lake Palcacocha has formed as a result of climate and glacier change of the past decades but is likely to persist for decades or even centuries into the future. Assignment of forward-looking responsibilities in case of climate-related loss and damage commonly

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implies remedying negative impacts or minimizing the risk of their occurrence, i.e. in case of Huaraz minimizing risks of GLOFs and their impacts (Wallimann-Helmer et al., 2019). Investigating the different risk drivers can be useful to identify what risk reduction measures need to be taken but it cannot identify the appropriate responsibility bearers, nor whether remedial responsibilities should concern monetary payments, help in building the required infrastructure and protection measures, assistance in governance or capacity building (O'Neill, 2017; Page and Heyward, 2016).

It seems plausible that industrialized countries and regions contributing most to anthropogenic climate change foster the development of appropriate infrastructure and capacity in order for the affected people to be able to govern local climate risk themselves (Wallimann-Helmer, 2016). In cases like Huaraz, this is particularly important for two reasons. Firstly, many locals moved to Huaraz and especially to Nueva Florida for social and economic reasons. As we have seen, relocation out of the GLOF hazard zone means to many a risk of losing social status and achieved assets, exacerbated by a lack of trust in the government to compensate people so that they can retain their achieved status. Capacity building here demands building trust in governance institutions and, if necessary, providing financial resources. Secondly, due to the socioeconomic opportunities provided by moving to Huaraz from rural areas as well as due to cultural beliefs, perceptions of GLOF risk are diverse and not necessarily congruent with technical and scientific findings. This makes the sharing and exchange of comprehensive information and education to inhabitants of Huaraz and especially to those living in the flood hazard zone another key factor of capacity building. Otherwise, there is a risk of decision-making by locals on the basis of insufficient information. Local or international experts may provide information on what can happen in case of a GLOF (e.g. flood height and extent in Huaraz). However, for reasons of efficiency and effectiveness, and of local appropriation and acceptance of measures, it is sensible to leave decisions about what constitutes an acceptable or tolerable risk and how risk governance is implemented to those people who are most directly affected (Kaswan, 2016). In fact, locals' perspectives (e.g. in terms of cultural and spiritual understandings) should be taken seriously, suggesting a dialogue of knowledges about GLOF risk and environmental change more broadly, rather than a hierarchical knowledge exchange.

Governance institutions and legal regulations define whether or not and to what extent individuals must bear responsibility for their own decisions with regard to settlements in risk zones like Nueva Florida. Institutions regulate behavior and demand justification if their regulations are not followed. However, institutions themselves are most often also responsibility bearers. The policy level at issue thereby defines the agent to take on responsibilities and the object of the responsibilities to be taken on (Wallimann-Helmer, 2019). Institutions are answerable to other, higher-level institutions and depend in their functioning on these institutions. For instance, the Glacier and Lake Evaluation Unit in Huaraz depends on finance and decisions from the central government in Lima through the National Water Authority (ANA), and according to available resources, this office can take on more or less ambitious responsibilities. Since responsible agents are always answerable towards some institution, the institutional inconsistencies and instabilities at Palcacocha tend to foster lax implementation of regulations on the side of the agents that should take on responsibility. Who bears the responsibilities to help establish, strengthen and maintain functioning institutions depends on the governance level and capacities of relevant responsibility bearers. Socio-economically disadvantaged locals might not be able to strengthen institutions but the wealthy ones and government officials may have this power. In case of Palcacocha, some technical and governmental institutions in conjunction with international assistance and

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565 cooperation may be best suited to do so, including the Ancash Regional Government and possibly the municipal government of Huaraz.

570 These considerations in relation with the Palcacocha case suggest that there may be at least two different perspectives of responsibility corresponding to two different approaches to fairness and justice, which, however, we consider neither as competing nor mutually exclusive. One of them aligns with the 'ability to pay' principle (Caney, 2005; Page, 2008) that proposes that capacity is the most important criterion for fairly differentiating responsibilities in the context of climate risk governance. One may argue that efficiency and effectiveness in risk governance is achieved if those agents and institutions with most capacity take on responsibility. This perspective would then also call for capacity building efforts where capacity is lacking. The other responsibility perspective is more guided by the 'polluter pays' principle (Gardiner, 2004; Hayward, 2012), implying that other responsibility bearers would have to carry heavier burdens. This leads to a more backward-looking approach to justice.

575 In global climate policy, the underlying premise has generally been that it is the industrialized countries (Annex I countries) that have heavily contributed to anthropogenic emissions and are thus assigned heavier burdens. Applying the logic and mechanisms of global climate policy to the Palcacocha case would foresee global emitters nourishing international climate funds (such as the Green Climate Fund), used to implement local adaptation and risk management measures. However, we also have seen that a substantial, yet again hardly quantifiable fraction of increased GLOF risk in Huaraz is due to socio-economic, institutional and cultural factors with a complex network of agents and responsibilities. How the different components and drivers of risk are weighted (e.g. as major or minor risk drivers) is eventually a societal or political process from which we abstain here. Notwithstanding, our analysis suggests that while global emitters bear responsibility for their contribution to locally materializing risks, local governments are not exempted from their responsibilities to address and effectively reduce the risk of negative GLOF impacts.

585 Defining the legal responsibilities for private company (or other) emitters (such as RWE in this case) needs to be determined by the court based on the respective laws and available evidence. In principle the contribution of single or corporate emitters (being countries or private companies) to specified components and drivers of GLOF hazard can be quantified (Stuart-Smith et al., 2020), (as it has also been suggested for other climatic extreme events (Otto et al., 2017), and it is reasonable to indicate an associated uncertainty margin.

590 **8 Conclusions**

595 Palcacocha is in many aspects representative for the interlinkages of global and local drivers of climate risks and potential or actual loss and damage. The case shows that risks develop, and loss and damage occur, in a local context and over a certain period of time. Comprehensively understanding the different contributors to risk is challenging and has only been addressed by research in a limited way so far. Risk (and associated loss and damage) is a multi-faceted construction and the question of causality can often not be fully solved, at least not in a quantitative way.

Here we have seen that an anthropogenic signal (related to GHG emissions) is traceable through an impact chain of temperature, glacier change and associated lake growth that has increased GLOF hazard in Huaraz over the past few decades.

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Long-term climate, glacier and lake observations, modeling, geotechnical and geomorphological analyses and flood modeling are needed to develop an understanding of the impact cascade. In contrast, the current conditions of exposure and vulnerability of people and values in Huaraz to GLOF hazard can only be understood with a historical perspective of social, economic, political and cultural dynamics.

Questions of responsibility, more broadly speaking, are difficult to be addressed in such cases where global, national and local drivers build a complex interlinked network. Courts, as in the case of Luciano Lliuya vs RWE, operate under specific rules of (national) law that we have not further analyzed here. For questions of responsibility, we have sketched how the Palcacocha case could be embedded in a normative framework where we distinguish between perspectives of efficiency (with respect to risk management) and backward-looking contributor pays principles. Rather than promoting one or the other principle we suggest a more differentiated and blended perspective on responsibility, implying that global emitters commit to support strengthening capacities in affected regions and localities, and local institutions and societies engage in local risk reduction measures and policies. In the case of Palcacocha and Huaraz a suite of measures are suggested, some of them being implemented over the past years. Structural measures such as flood protection dams and lake drainage can effectively reduce flood hazard levels, a GLOF early warning system can help save lives, increase awareness and strengthen institutional prevention and response capacities. More rigorous land-use planning would be a highly effective risk reduction measures but we have seen the significant associated social, economic, political and institutional barriers, in particular when communities are not involved directly and meaningfully in such policymaking. Comprehensive efforts for a dialogue of risk knowledges could have positive, long-term risk reduction effects.

After all, and beyond the case of Palcacocha and GLOF's in general, we believe that an improved understanding of drivers of risk and explicit differentiation of responsibilities can contribute to more effectively addressing climate risk and loss and damage.

Data availability

The socio-economic and population data can be accessed from the National Statistical Institute of Peru, INEI: <http://sige.inei.gob.pe/sige/>. Satellite data is available from Google Earth; historical aerial imagery, results of hazard modeling runs and lake volume data can be requested from the corresponding author.

Competing interests

Two authors had paid and unpaid working relation with Germanwatch, the non-governmental organization that supports Saúl Lliuya in the court case Lliuya vs RWE. Specifically, N.W.C. had an internship with Germanwatch (2 months, 2014), followed by short-termed consultancies (2014 to 2020) and employment in 2016. A.E. prepared scientific material for Germanwatch on a short-term paid basis, and C.H. made an expert statement for the Lliuya party of the court case on an unpaid basis.

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Author contributions

CH developed and led the study, wrote and edited text, analyzed the climate change attribution part, did the socio-economic data analysis and produced figures. AE contributed the sections and data on the lake development, HF the GLOF modeling and hazard assessments, and both contributed figures. MC and NW-C contributed and wrote the section on socio-economic, institutional and cultural aspects of risks. IW-H led the section on justice and responsibility. All authors revised and edited the manuscript.

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Table

Period / date	Milestone	Details	Reference
1590 - 1630	Glacier advance and formation of the moraine	Formation of the moraine which (later) dammed the lake	(Emmer, 2017)
late 1930s	European expeditions to the lake and the first photographs	Hanz Kinzl visited Palcacocha and other Cordillera Blanca glaciers and glacier lakes (1939)	(Byers, 2000; Carey, 2012; Wegner, 2014)
13th December 1941	Dam failure and GLOF	See main text	(Carey, 2010; Oppenheim, 1946)
1950s - 1960s	Lake stagnation	1942: clearance of drainage canal to facilitate drainage 1950s: construction of a security dam with a drainage canal at its base to prevent rising lake levels level. Minimal lake growth/stagnation	Air photographs; Carey 2010
31st May 1970	Heavy earthquake	M=7.9 earthquake hit the region, no recorded damages on the dam	(Lliboutry et al., 1977)
1973 - 1974	Remediation	Lowering lake level by 1 m and stabilizing it at 4,566 m a.s.l.; reinforced and rebuilt the 1950s security dam, including a permanent drainage canal; construction of a second security dam on the terminal moraine	(ELECTROPERÚ, 1974)
1974	Bathymetry	Volume $0.515 \cdot 10^6 \text{ m}^3$	ELECTROPERÚ, 1974
1970s - 2000s	Lake growth	See main text	Zapata et al., 2004
2003	Dam overtopping and GLOF	Landslide on left lateral moraine into the lake; partial destruction of secondary security dam, which was rebuilt in 2004	(Vilimek et al., 2005)
2003	Bathymetry	Volume $3.690 \cdot 10^6 \text{ m}^3$	(Zapata et al., 2004)
2003 - present	Accelerated lake growth	See main text	(UGRH, 2016)
2009	Bathymetry	Volume $17.325 \cdot 10^6 \text{ m}^3$	(Portocarrero, 2014)
2011	Remediation	A set of siphons was installed to lower lake level prior to the implementation of permanent solution	Portocarrero, 2014
2016	Bathymetry	Volume $17.403 \cdot 10^6 \text{ m}^3$	UGRH, 2016
August 2018	Remediation	Lake level lowered by 3 m	Field visits

1165 **Table 1: Milestones in the evolution of Lake Palcacocha.**

Figures

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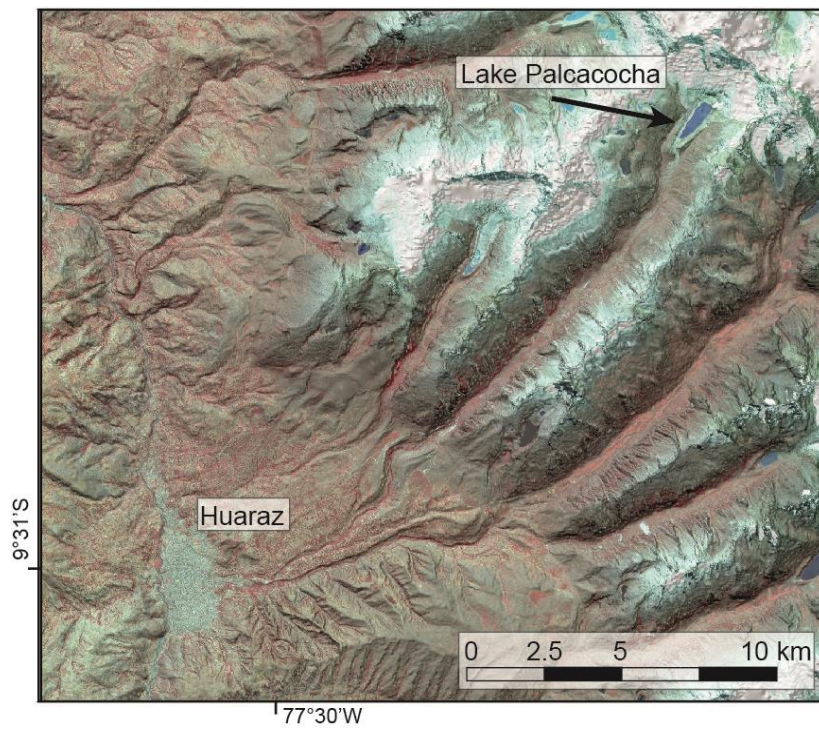


Figure 1: Study region with Lake Palcacocha and the city of Huaraz (source SPOT image, year of acquisition: 2006).

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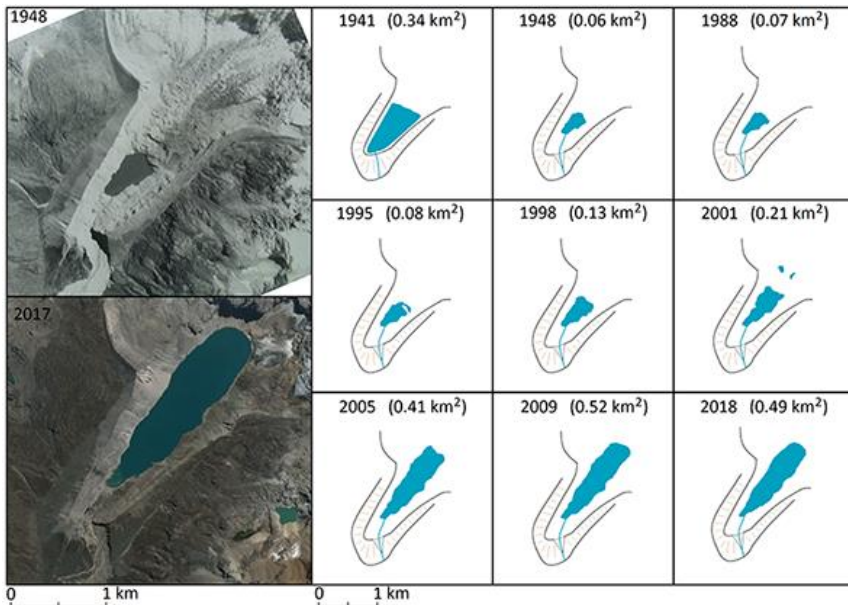
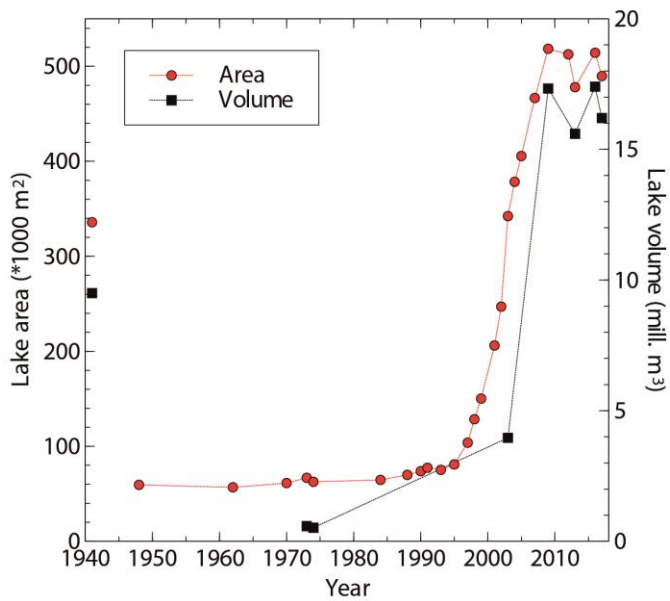
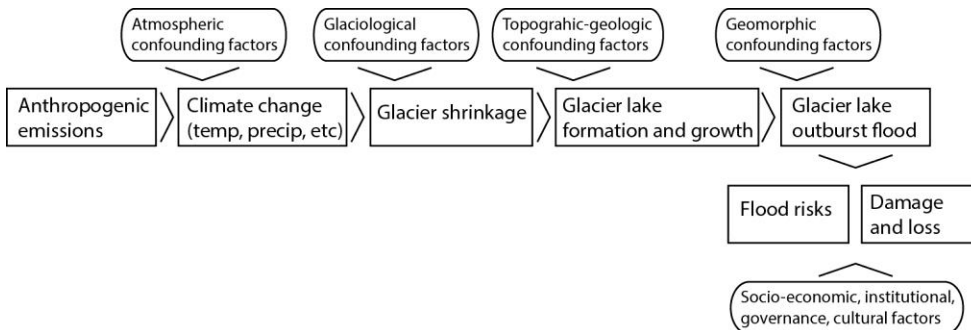


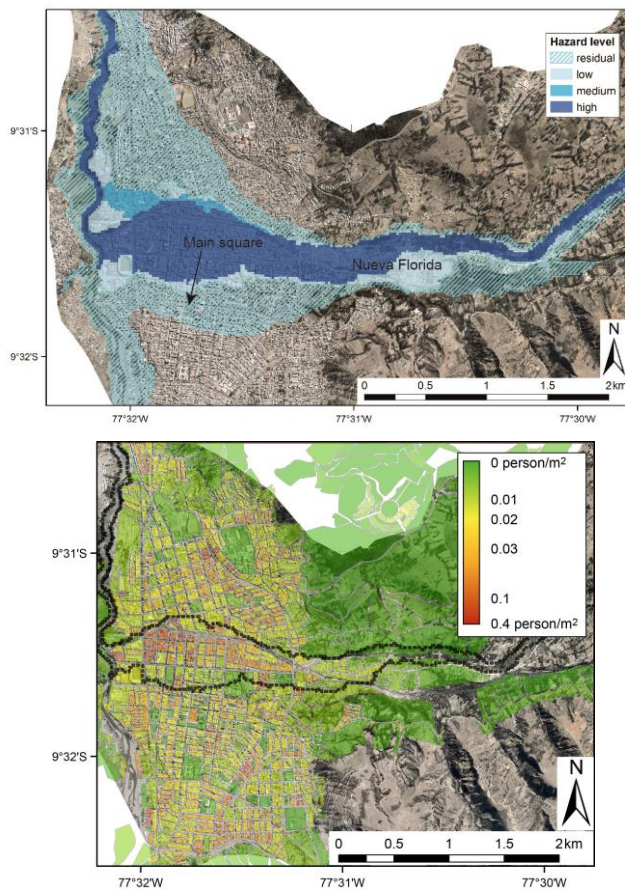
Figure 2: Evolution of Lake Palcacocha from 1941 to present (source of 1948 image: Archives of the Autoridad Nacional de Agua, Peru, source of 2017 image: CNES/Airbus image, Google Earth, date of acquisition: 18 June 2017, source of lake evolution 1988-2018: Landsat images).



1180 **Figure 3: Evolution of area and volume of lake Palcacocha 1941 to present (data sources: see Table 1).**



1185 **Figure 4: Causation chain from anthropogenic emissions to glacier lake flood risk. At each element of the causation chain non-climatic (confounding) factors are indicated which also influence the respective element.**



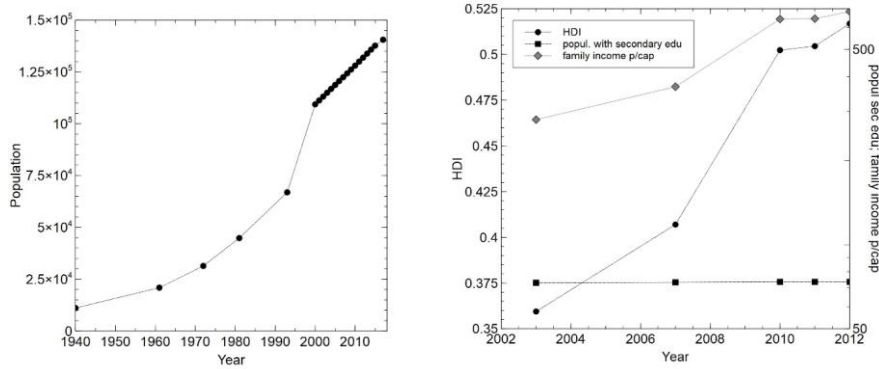
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Figure 5: **Top panel:** Hazard map for the city of Huaraz as related to GLOFs from Lake Palcacocha. The district of Nueva Florida and the main square of the city are indicated (for a more detailed description of the hazard mapping methodology see supplementary material) (source of image: Google Earth / Maxar Technologies, date of acquisition: 11/10/2017). **Bottom panel:** population distribution for the same extent of Huaraz. Also indicated is the extent of the high hazard zone (dark blue in the top panel map) (source of population data: INED).



Figure 6: Aerial photograph from 1948 showing the traces of the 1941 GLOF (upper panel), and 2016 satellite image of the same area (lower panel). The outlines in orange indicate the extent of the area affected by the 1941 GLOF. The

1205 highly flood exposed urban district of Nueva Florida is indicated (source of upper image: Archive of Autoridad Nacional de Agua, Peru, year of acquisition: 1948; lower image: Google Earth / Maxar Technologies, 11/10/2017).



1210 **Figure 7: Population growth of Huaraz over the period 1941-2017. Data since the year 2000 is based on an extrapolation produced by the National Statistical Office of Peru (INEI) (left panel). Vulnerability indicators and their changes between 2002 and 2012 for the city of Huaraz. HDI: human development index, percentage of population with secondary education, and family income per capita in Nuevo Soles per month (data from INEI) (right panel).**

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