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

Christian Huggel[1], Mark Carey[2], Adam Emmer[3], Holger Frey[1], Noah Walker-Crawford[4], Ivo Wallimann-Helmer[5]
[1]Department of Geography, University of Zurich, Winterthurerstrasse 190, CH-8057 Zurich, Switzerland
[2]Robert D. Clark Honors College and Environmental Studies Program, University of Oregon, USA
[3]The Czech Academy of Science, Global Change Research Institute, 603 00 Brno, Czech Republic
[4]Department of Social Anthropology, Manchester University, UK
[5]University of Fribourg Environmental Sciences and Humanities Institute, Switzerland

Correspondence to: Christian Huggel (christian.huggel@geo.uzh.ch)

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.

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.

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

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 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 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 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 (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 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 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 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 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

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 us to clarify the differentiation of responsibilities and the challenges ahead vis-à-vis impacts and risks of loss and damage.

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.) 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 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 m^3 and peak discharge in excess of 10,000 m^3/s, producing devastating 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 related to piping in the dam (Oppenheim, 1946).

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 (Lliboutry 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 the lake water level by 1 m, and stabilizing it at 4,566 m a.s.l. with 7 m of freeboard and $0.515 \cdot 10^6$ m^3 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).

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 $3.690 \cdot 10^6$ 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 $17.325 \cdot 10^6$ 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.

With a volume of $17.403 \cdot 10^6$ 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.

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).

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, 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, 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 (Kinzl, 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).

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).

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 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.

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).

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 (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.

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 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

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).

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.

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. Anonymous, 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.

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 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).

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.

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 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.

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 m^3 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).

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

(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

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

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.

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).

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.

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

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.

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.

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.

8 Conclusions

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.

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.WC. 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.

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.

Acknowledgements

We acknowledge the collaboration and exchange with CARE Peru, the Glacier and Lakes Evaluation Office of the National Water Authority (ANA) and the National Institute for Glacier and Mountain Ecosystem Research (INAIGEM), as well as with the local residents. We thank Marcelo Somos-Valenzuela for facilitating data on population distribution in Huaraz. Finally, we would like to acknowledge the constructive review comments by Dmitry Petrakov and Marcus Nüsser, and the comments by and exchange with Will Frank, Rupert Stuart-Smith and Gerard Roe, which all helped to improve the paper.

References

Allen, S. K., Rastner, P., Arora, M., Huggel, C. and Stoffel, M.: Lake outburst and debris flow disaster at Kedarnath, June 2013: hydrometeorological triggering and topographic predisposition, Landslides, 13(6), 1479–1491, doi:10.1007/s10346-015-0584-3, 2016.

Allison, E. A.: The spiritual significance of glaciers in an age of climate change, Wiley Interdiscip. Rev. Clim. Change, 6(5), 493–508, doi:10.1002/wcc.354, 2015.

Anonymous: La reconstrucción de la zona del aluvión, El Departamento, Huaraz., 1945.

Anonymous: Edificaciones en el Aluvión, El Departamento, Huaraz., 1951.

Anonymous: Urbanisación de la zona del aluvión, El Departamento, Huaraz., 1956.

Arce, M.: The Repoliticization of Collective Action after Neoliberalism in Peru, Lat. Am. Polit. Soc., 50(3), 37–62, 2008.

Bayertz, K.: Eine kurze Geschichte der Herkunft der Verantwortung, in K. Bayertz (Ed.), Verantwortung. Prinzip oder Problem?, pp. 3–71, Wissenschaftliche Buchgesellschaft, Darmstadt., 1995.

Bindoff, N. L., Stott, P. A., AchutaRao, K. M., Allen, M. R., Gillett, N., Gutzler, D., Hansingo, K., Hegerl, G., Hu, Y. and Jain, S.: Detection and attribution of climate change: from global to regional, in Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (Ed.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change., pp. 867–952, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., 2013.

Bindoff, N. L., P. A. Stott, K. M. AchutaRao, M. R. Allen, N. Gillett, D. Gutzler, K. Hansingo, G. Hegerl, Y. Hu, S. Jain, I. I. Mokhov, J. Overland, J. Perlwitz, R. Sebbari and X. Zhang: Detection and Attribution of Climate Change: from Global to Regional, in Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by T. F. Stocker D. Qin, G. K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley, pp. 867–952, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., 2013.

Blaikie, P. M., Cannon, T., Davis, I. and Wisner, B.: At risk: natural hazards, people’s vulnerability, and disasters, Routledge London., 1994.

Bode, B.: Disaster, Social Structure, and Myth in the Peruvian Andes: The Genesis of an Explanation, Ann. N. Y. Acad. Sci., 293, 246–274, 1977.

Bode, B.: No Bells to Toll: Destruction and Creation in the Andes, Paragon House, New York., 1990.

Bolin, I.: The Glaciers of the Andes are Melting: Indigenous and Anthropological Knowledge Merge in Restoring Water Resources, in Anthropology and Climate Change: From Encounters to Actions, edited by S. A. Crate and M. Nuttall, pp. 228–239, Left Coast Press, Walnut Creek, CA., 2009.

Burns, W. C. and Osofsky, H. M.: Adjudicating climate change: state, national, and international approaches, Cambridge University Press. [online] Available from: https://books.google.ch/books?hl=de&lr=&id=_JLO0URFjOoC&oi=fnd&pg=PR5&dq=grossman+liability+adjudicating+climate+change+cambridge&ots=nM6e3UB5cG&sig=9NnQR155vcPSCwbtms3OBrzYJzI (Accessed 2 September 2015), 2009.

Byers, A. C.: Contemporary landscape change in the Huascarán National Park and buffer zone, Cordillera Blanca, Peru, Mt. Res. Dev., 20(1), 52–63, 2000.

Calliari, E.: Loss and damage: a critical discourse analysis of Parties’ positions in climate change negotiations, J. Risk Res., 21(6), 725–747, doi:10.1080/13669877.2016.1240706, 2018.

Caney, S.: Cosmopolitan Justice, Responsibility, and Global Climate Change, Leiden J. Int. Law, 18(04), 747–775, 2005.

Carey, M.: Living and dying with glaciers: people’s historical vulnerability to avalanches and outburst floods in Peru, Glob. Planet. Change, 47(2–4), 122–134, 2005.

Carey, M.: Mountaineers and Engineers: An Environmental History of International Sport, Science, and Landscape Consumption in Twentieth-Century Peru, Hisp. Am. Hist. Rev., 92(1), 107–141, 2012.

Carey, M., Huggel, C., Bury, J., Portocarrero, C. and Haeberli, W.: An integrated socio-environmental framework for climate change adaptation and glacier hazard management: Lessons from Lake 513, Cordillera Blanca, Peru, Clim. Change, 112(3–4), 733–767, 2012.

Carey, M., McDowell, G., Huggel, C., Jackson, M., 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. In: W. Haeberli, C. Whiteman, J.F.Shroder (Eds.). Hazards and Disasters Series., pp. 221–261, Elsevier, Oxford, UK., 2014.

Carey, M., Molden, O. C., Rasmussen, M. B., Jackson, M., Nolin, A. W. and Mark, B. G.: Impacts of Glacier Recession and Declining Meltwater on Mountain Societies, Ann. Am. Assoc. Geogr., 107(2), 350–359, doi:10.1080/24694452.2016.1243039, 2017.

Carey, M. P.: In the shadow of melting glaciers: climate change and Andean Society, Oxford University Press, USA., 2010.

Carrivick, J. L. and Tweed, F. S.: A global assessment of the societal impacts of glacier outburst floods, Glob. Planet. Change, 144, 1–16, doi:10.1016/j.gloplacha.2016.07.001, 2016.

Casassa, G., López, P., Pouyaud, B. and Escobar, F.: Detection of changes in glacial run-off in alpine basins: examples from North America, the Alps, central Asia and the Andes, Hydrol. Process., 23(1), 31–41, doi:10.1002/hyp.7194, 2009.

Costa, J. E. and Schuster, R. L.: The formation and failure of natural dams, Geol. Soc. Am. Bull., 7, 1054–1068, 1988.

Cramer, W., G.W. Yohe, M. Auffhammer, C. Huggel, U. Molau, M.A.F. Silva Dias, A. Solow, D.A. Stone and Tibig, L.: Detection and attribution of observed impacts, in Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change, edited by C. B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L. L. White, pp. 979–1037, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., 2014.

Cruikshank, J.: Do glaciers listen?, University of British Columbia Press, Vancouver, Canada., 2005.

De la Cadena, M.: Earth beings: Ecologies of practice across Andean worlds, Duke University Press, Durham and London., 2015.

Dickovick, J. T.: Decentralization and Recentralization in the Developing World: Comparative Studies from Africa and Latin America, Penn State University Press, University Park., 2011.

Doughty, P. L.: Plan and Pattern in Reaction to Earthquake: Peru, 1970-1998, in The Angry Earth: Disaster in Anthropological Perspective, edited by A. Oliver-Smith and S. M. Hoffman, pp. 234–256, Routledge, New York., 1999.

Drew, G.: A Retreating Goddess? Conflicting Perceptions of... - Google Scholar, Nat. Cult., 6, 344–362, 2012.

Dussaillant, I., Berthier, E., Brun, F., Masiokas, M., Hugonnet, R., Favier, V., Rabatel, A., Pitte, P. and Ruiz, L.: Two decades of glacier mass loss along the Andes, Nat. Geosci., 12(10), 802–808, doi:10.1038/s41561-019-0432-5, 2019.

El Comercio: Elecciones 2018: La agenda pendiente en Ancash, Grupo El Comercio. Accessed 18 December 2018. https://elcomercio.pe/peru/ancash/agenda-pendiente-ancash-noticia-561183., 2018.

ELECTROPERÚ: Liquidacion de Obra “Consolidacion Laguna Palcacocha“ 1973-1974, ELECTROPERU, Huaraz, Perú., 1974.

Emmer, A.: Geomorphologically effective floods from moraine-dammed lakes in the Cordillera Blanca, Peru, Quat. Sci. Rev., 177, 220–234, doi:10.1016/j.quascirev.2017.10.028, 2017.

Emmer, A. and Vilímek, V.: Review Article: Lake and breach hazard assessment for moraine-dammed lakes: an example from the Cordillera Blanca (Peru), Nat Hazards Earth Syst Sci, 13(6), 1551–1565, doi:10.5194/nhess-13-1551-2013, 2013.

Emmer, A., Klimeš, J., Mergili, M., Vilímek, V. and Cochachin, A.: 882 lakes of the Cordillera Blanca: An inventory, classification, evolution and assessment of susceptibility to outburst floods, CATENA, 147, 269–279, doi:10.1016/j.catena.2016.07.032, 2016.

Emmer, A., Vilímek, V. and Zapata, M. L.: Hazard mitigation of glacial lake outburst floods in the Cordillera Blanca (Peru): the effectiveness of remedial works, J. Flood Risk Manag., 11(S1), S489–S501, doi:10.1111/jfr3.12241, 2018.

Faillettaz, J., Funk, M. and Vincent, C.: Avalanching glacier instabilities: Review on processes and early warning perspectives, Rev. Geophys., 53(2), 2014RG000466, doi:10.1002/2014RG000466, 2015.

Frank, W., Bals, C. and Grimm, J.: The Case of Huaraz: First Climate Lawsuit on Loss and Damage Against an Energy Company Before German Courts, in Loss and Damage from Climate Change: Concepts, Methods and Policy Options, edited by R. Mechler, L. M. Bouwer, T. Schinko, S. Surminski, and J. Linnerooth-Bayer, pp. 475–482, Springer International Publishing, Cham., 2019.

Frey, H., Huggel, C., Chisolm, R. E., Baer, P., McArdell, B., Cochachin, A. and Portocarrero, C.: Multi-Source Glacial Lake Outburst Flood Hazard Assessment and Mapping for Huaraz, Cordillera Blanca, Peru, Front. Earth Sci., 6, doi:10.3389/feart.2018.00210, 2018.

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

Ganguly, G., Setzer, J. and Heyvaert, V.: If at First You Don’t Succeed: Suing Corporations for Climate Change, Oxf. J. Leg. Stud., 38(4), 841–868, doi:10.1093/ojls/gqy029, 2018.

Gardiner, S. M.: Ethics and Global Climate Change, Ethics, 114, 555–600, 2004.

Georges, C.: 20th-century glacier fluctuations in the tropical Cordillera Blanca, Peru, Arct. Antarct. Alp. Res., 36(1), 100–107, 2004.

Grossman, D. A.: Warming up to a Not-So-Radical Idea: Tort-Based Climate Change Litigation, Columbia J. Environ. Law, 28, 1, 2003.

Haeberli, W., Schaub, Y. and Huggel, C.: Increasing risks related to landslides from degrading permafrost into new lakes in de-glaciating mountain ranges, Geomorphology, 293(Part B), 405–417, doi:10.1016/j.geomorph.2016.02.009, 2017.

Hansen, G. and Stone, D.: Assessing the observed impact of anthropogenic climate change, Nat. Clim. Change, 6(5), 532–537, doi:10.1038/nclimate2896, 2016.

Harrison, S., Kargel, J. S., Huggel, C., Reynolds, J., Shugar, D. H., Betts, R. A., Emmer, A., Glasser, N., Haritashya, U. K., Klimeš, J., Reinhardt, L., Schaub, Y., Wiltshire, A., Regmi, D. and Vilímek, V.: Climate change and the global pattern of moraine-dammed glacial lake outburst floods, The Cryosphere, 12(4), 1195–1209, doi:10.5194/tc-12-1195-2018, 2018.

Hastenrath, S. and Ames, A.: Recession of Yanamarey Glacier in Cordillera Blanca, Peru, during the 20th century, J. Glaciol., 41(137), 191–196, doi:10.3189/S0022143000017883, 1995.

Hastrup, K.: Anthropological contributions to the study of climate: past, present, future, Wiley Interdiscip. Rev. Clim. Change, 4(4), 269–281, doi:10.1002/wcc.219, 2013.

Hayward, T.: Climate change and ethics, Nat. Clim. Change, 2(12), 843–848, 2012.

Hegglin, E. and Huggel, C.: An Integrated Assessment of Vulnerability to Glacial Hazards, Mt. Res. Dev., 28(3), 299–309, 2008.

Heidinger, H., Carvalho, L., Jones, C., Posadas, A. and Quiroz, R.: A new assessment in total and extreme rainfall trends over central and southern Peruvian Andes during 1965–2010, Int. J. Climatol., 38(S1), e998–e1015, doi:10.1002/joc.5427, 2018.

Hock, R. and et al.: High Mountain Areas, in IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, M. Nicolai, A. Okem, J. Petzold, B. Rama, N. Weyer (eds.)]., 2019.

Hoegh - Guldberg, O., Jacob, D., Taylor, M., Bindi, M., Brown, S., Camilloni, I., Diedhiou, A., Djalante, R., Ebi, K., Engelbrecht, F., Guiot, K., Hijioka, Y., Mehrotra, S., Payne, A., Seneviratne, S., Thomas, A., Warren, R. and Zhou, G.: Impacts of 1.5ºC Global Warming on Natural and Human Systems., in Impacts of 1.5ºC Global Warming on Natural and Human Systems. In: 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, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]., pp. 175–311, Intergovernmental Panel on Climate Change. [online] Available from: http://pure.iiasa.ac.at/id/eprint/15518/ (Accessed 20 January 2019), 2018.

Huggel, C., Wallimann-Helmer, I., Stone, D. and Cramer, W.: Reconciling justice and attribution research to advance climate policy, Nat. Clim. Change, 6(10), 901–908, doi:10.1038/nclimate3104, 2016.

Huggel, C., Muccione, V., Carey, M., James, R., Jurt, C. and Mechler, R.: Loss and Damage in the mountain cryosphere, Reg. Environ. Change, 19, 1387–1399, doi:10.1007/s10113-018-1385-8, 2019.

Huss, M. and Hock, R.: Global-scale hydrological response to future glacier mass loss, Nat. Clim. Change, 8(2), 135–140, doi:10.1038/s41558-017-0049-x, 2018.

IPCC: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by C. B. Field, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., 2014.

James, R. A., Jones, R. G., Boyd, E., Young, H. R., Otto, F. E. L., Huggel, C. and Fuglestvedt, J. S.: Attribution: How Is It Relevant for Loss and Damage Policy and Practice?, in Loss and Damage from Climate Change: Concepts, Methods and Policy Options, edited by R. Mechler, L. M. Bouwer, T. Schinko, S. Surminski, and J. Linnerooth-Bayer, pp. 113–154, Springer International Publishing, Cham., 2019.

Jones, G. S., Stott, P. A. and Christidis, N.: Attribution of observed historical near–surface temperature variations to anthropogenic and natural causes using CMIP5 simulations, J. Geophys. Res. Atmospheres, 118(10), 4001–4024, doi:10.1002/jgrd.50239, 2013.

Jurt, C., Brugger, J., Dunbar, K. W., Milch, K. and Orlove, B.: Cultural values of glaciers, in The High-Mountain Cryosphere, C. Huggel, M. Carey, J.J. Clague and A. Kääb (Eds.), pp. 90–106, Cambridge University Press, Cambridge and New York., 2015.

Kääb, A. and Haeberli, W.: Evolution of a high-mountain thermokarst lake in the Swiss Alps, Arct. Antarct. Alp. Res., 385–390, 2001.

Kargel, J. S., Furfaro, R., Kaser, G., Leonard, G. J., Fink, W., Huggel, C., Kääb, A., Raup, B. H., Reynolds, J. M. and Zapata, M.: ASTER imaging and analysis of glacier hazards, in B. Ramachandran, C. O. Justice, and M.J. Abrams, (eds.), Land Remote Sensing and Global Environmental Change: NASA's Earth Observing System and the Science of Terra and Aqua, pp. 325–373, Springer, New York., 2011.

Kaser, G. and Georges, C.: Changes in the equilibrium line altitude in the tropical Cordillera Blanca (Perú) between 1930 and 1950 and their spatial variations, Ann. Glaciol., 24(24), 344–349, 1997.

Kaswan, A.: Climate Adaptation and Theories of Justice, Arch. Für Rechts- Sozialphilosophie, Beihefte 149, 97–118, 2016.

Kinzl, H.: La glaciacion actual y pleistocenica en los Andes centrales, Bol Soc Geog Lima, 89, 89–100, 1969.

Klimeš, J., Novotný, J., Novotná, I., de Urries, B. J., Vilímek, V., Emmer, A., Strozzi, T., Kusák, M., Rapre, A. C., Hartvich, F. and Frey, H.: Landslides in moraines as triggers of glacial lake outburst floods: example from Palcacocha Lake (Cordillera Blanca, Peru), Landslides, 13(6), 1461–1477, doi:10.1007/s10346-016-0724-4, 2016.

Kraaijenbrink, P. D. A., Bierkens, M. F. P., Lutz, A. F. and Immerzeel, W. W.: Impact of a global temperature rise of 1.5 degrees Celsius on Asia's glaciers, Nature, 549(7671), 257–260, doi:10.1038/nature23878, 2017.

Lees, E.: Responsibility and liability for climate loss and damage after Paris, Clim. Policy, 17(1), 59–70, doi:10.1080/14693062.2016.1197095, 2017.

Lliboutry, L., Morales Arnao, B., Pautre, A. and Schneider, B.: Glaciological problems set by the control of dangerous lakes in Cordillera Blanca, Peru, J. Glaciol., 18(79), 239–290, 1977.

Magrin, G. O., J.A. Marengo, J.-P. Boulanger, M.S. Buckeridge, E. Castellanos, G. Poveda, F.R. Scarano and Vicuña, S.: Central and South America, in Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change, edited by V. R. Barros, C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L. L. White, pp. 1499–1566, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., 2014.

Marjanac, S. and Patton, L.: Extreme weather event attribution science and climate change litigation: an essential step in the causal chain?, J. Energy Nat. Resour. Law, 0(0), 1–34, doi:10.1080/02646811.2018.1451020, 2018.

Marzeion, B., Cogley, J. G., Richter, K. and Parkes, D.: Attribution of global glacier mass loss to anthropogenic and natural causes, Science, 345(6199), 919–921, doi:10.1126/science.1254702, 2014.

McCormick, S., Glicksman, R. L., Simmens, S. J., Paddock, L., Kim, D. and Whited, B.: Strategies in and outcomes of climate change litigation in the United States, Nat. Clim. Change, 8(9), 829–833, doi:10.1038/s41558-018-0240-8, 2018.

McDowell, G., Huggel, C., Frey, H., Wang, F. M., Cramer, K. and Ricciardi, V.: Adaptation action and research in glaciated mountain systems: Are they enough to meet the challenge of climate change?, Glob. Environ. Change, 54, 19–30, doi:10.1016/j.gloenvcha.2018.10.012, 2019.

Mechler, R., Calliari, E., Bouwer, L. M., Schinko, T., Surminski, S., Linnerooth-Bayer, J., Aerts, J., Botzen, W., Boyd, E., Deckard, N. D., Fuglestvedt, J. S., González-Eguino, M., Haasnoot, M., Handmer, J., Haque, M., Heslin, A., Hochrainer-Stigler, S., Huggel, C., Huq, S., James, R., Jones, R. G., Juhola, S., Keating, A., Kienberger, S., Kreft, S., Kuik, O., Landauer, M., Laurien, F., Lawrence, J., Lopez, A., Liu, W., Magnuszewski, P., Markandya, A., Mayer, B., McCallum, I., McQuistan, C., Meyer, L., Mintz-Woo, K., Montero-Colbert, A., Mysiak, J., Nalau, J., Noy, I., Oakes, R., Otto, F. E. L., Pervin, M., Roberts, E., Schäfer, L., Scussolini, P., Serdeczny, O., de Sherbinin, A., Simlinger, F., Sitati, A., Sultana, S., Young, H. R., van der Geest, K., van den Homberg, M., Wallimann-Helmer, I., Warner, K. and Zommers, Z.: Science for Loss and Damage. Findings and Propositions, in Loss and Damage from Climate Change: Concepts, Methods and Policy Options, edited by R. Mechler, L. M. Bouwer, T. Schinko, S. Surminski, and J. Linnerooth-Bayer, pp. 3–37, Springer International Publishing, Cham., 2019.

Mergili, M., Pudasaini, S. P., Emmer, A., Fischer, J.-T., Cochachin, A. and Frey, H.: Reconstruction of the 1941 GLOF process chain at Lake Palcacocha (Cordillera Blanca, Peru), Hydrol. Earth Syst. Sci., 24(1), 93–114, doi:https://doi.org/10.5194/hess-24-93-2020, 2020.

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, Reg. Environ. Change, 19(5), 1311–1326, doi:10.1007/s10113-019-01484-w, 2019.

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, edited by P. Meusburger, T. Freytag, and L. Suarsana, pp. 191–209, Springer International Publishing, Cham., 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, Reg. Environ. Change, 19(5), 1327–1337, doi:10.1007/s10113-018-1372-0, 2019.

Okereke, C., Baral, P. and Dagnet, Y.: Options for adaptation and loss & damage in a 2015 climate agreement, in Working Paper, p. 19 pp., Agreement for Climate Transformation 2015 (ACT15), Washington D.C., 2014.

Oliver-Smith, A.: Traditional Agriculture, Central Places, and Postdisaster Urban Relocation in Peru, Am. Ethnol., 4(1), 102–116, 1977.

Oliver-Smith, A.: Here There is Life: The Social and Cultural Dynamics of Successful Resistance to Resettlement in Postdisaster Peru, in Involuntary Migration and Resettlement: The Problems and Responses of Dislocated People, edited by A. Hansen and A. Oliver-Smith, pp. 85–103, Westview Press, Boulder, Col., 1982.

Oliver-Smith, A.: The Martyred City: Death and Rebirth in the Andes, University of New Mexico Press, Albuquerque., 1986.

Oliver-Smith, A.: Peru’s Five-Hundred-Year Earthquake: Vulnerability in Historical Context, in The Angry Earth: Disaster in Anthropological Perspective, edited by A. Oliver-Smith and S. M. Hoffman, pp. 74–88, Routledge, New York., 1999.

Oliver-Smith, A.: A matter of choice, Int. J. Disaster Risk Reduct., 3, 1–3, doi:10.1016/j.ijdrr.2012.12.001, 2013.

O’Neill, J.: The price of an apology: justice, compensation and rectification, Camb. J. Econ., 41(4), 1043–1059, doi:10.1093/cje/bew047, 2017.

Oppenheim, V.: Sobre las lagunas de Huaráz, Boletin Soc. Geol. Peru Soc. Geol. Peru Lima, 68–80, 1946.

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, Reg. Environ. Change, 19(5), 1295–1309, doi:10.1007/s10113-019-01482-y, 2019.

Otto, F. E. L., Skeie, R. B., Fuglestvedt, J. S., Berntsen, T. and Allen, M. R.: Assigning historic responsibility for extreme weather events, Nat. Clim. Change, 7(11), 757–759, doi:10.1038/nclimate3419, 2017.

Page, E.: Distributing the Burdens of Climate Change, Environ. Polit., 17(4), 556–575, 2008.

Page, E. A. and Heyward, C.: Compensating for Climate Change Loss and Damage, Polit. Stud., 65(2), 356–372, doi:10.1177/0032321716647401, 2016.

Portocarrero, C. A.: Reducing the risk of dangerous lakes in the Peruvian Andes: A handbook for glacial lake management, US Agency for International Development (USAID), Washington DC., 2014.

Rabatel, A., Francou, B., Soruco, A., Gomez, J., Cáceres, B., Ceballos, J. L., Basantes, R., Vuille, M., Sicart, J.-E., Huggel, C., Scheel, M., Lejeune, Y., Arnaud, Y., Collet, M., Condom, T., Consoli, G., Favier, V., Jomelli, V., Galarraga, R., Ginot, P., Maisincho, L., Mendoza, J., Ménégoz, M., Ramirez, E., Ribstein, P., Suarez, W., Villacis, M. and Wagnon, P.: Current state of glaciers in the tropical Andes: a multi-century perspective on glacier evolution and climate change, The Cryosphere, 7(1), 81–102, doi:10.5194/tc-7-81-2013, 2013.

Raetzo, H. Raetzo, Lateltin, O. Lateltin, Bollinger, D. Bollinger, Tripet and J. Tripet: Hazard assessment in Switzerland – Codes of Practice for mass movements, Bull. Eng. Geol. Environ., 61(3), 263–268, doi:10.1007/s10064-002-0163-4, 2002.

Schauwecker, S., Rohrer, M., Acuña, D., Cochachin, A., Dávila, L., Frey, H., Giráldez, C., Gómez, J., Huggel, C., Jacques-Coper, M., Loarte, E., Salzmann, N. and Vuille, M.: Climate trends and glacier retreat in the Cordillera Blanca, Peru, revisited, Glob. Planet. Change, 119, 85–97, doi:10.1016/j.gloplacha.2014.05.005, 2014.

Schauwecker, S., Rohrer, M., Huggel, C., Endries, J., Montoya, N., Neukom, R., Perry, B., Salzmann, N., Schwarb, M. and Suarez, W.: The freezing level in the tropical Andes, Peru: an indicator for present and future glacier extents, J. Geophys. Res. Atmospheres, 2016JD025943, doi:10.1002/2016JD025943, 2017.

Schneider, D., Huggel, C., Cochachin, A., Guillén, S. and García, J.: Mapping hazards from glacier lake outburst floods based on modelling of process cascades at Lake 513, Carhuaz, Peru, Adv Geosci, 35, 145–155, doi:10.5194/adgeo-35-145-2014, 2014.

Sherpa, P.: Climate Change, Perceptions, and Social Heterogeneity in Pharak, Mount Everest Region of Nepal, Hum. Organ., 73(2), 153–161, doi:10.17730/humo.73.2.94q43152111733t6, 2014.

Sherry, J., Curtis, A., Mendham, E. and Toman, E.: Cultural landscapes at risk: Exploring the meaning of place in a sacred valley of Nepal, Glob. Environ. Change, 52, 190–200, doi:10.1016/j.gloenvcha.2018.07.007, 2018.

Somos-Valenzuela, M. A.: Vulnerability and decision risk analysis in glacier lake outburst floods (GLOF). Case studies : Quillcay sub basin in the Cordillera Blanca in Peru and Dudh Koshi sub basin in the Everest region in Nepal, Thesis, August. [online] Available from: https://repositories.lib.utexas.edu/handle/2152/25940 (Accessed 29 December 2018), 2014.

Somos-Valenzuela, M. A., Chisolm, R. E., Rivas, D. S., Portocarrero, C. and McKinney, D. C.: Modeling a glacial lake outburst flood process chain: the case of Lake Palcacocha and Huaraz, Peru, Hydrol Earth Syst Sci, 20(6), 2519–2543, doi:10.5194/hess-20-2519-2016, 2016.

Steinberg, T.: Acts of God: The Unnatural History of Natural Disaster in America, Oxford University Press, New York., 2000.

Stone, D., Auffhammer, M., Carey, M., Hansen, G., Huggel, C., Cramer, W., Lobell, D., Molau, U., Solow, A., Tibig, L. and Yohe, G.: The challenge to detect and attribute effects of climate change on human and natural systems, Clim. Change, 121(2), 381–395, doi:10.1007/s10584-013-0873-6, 2013.

Stott, P. A., Tett, S. F. B., Jones, G. S., Allen, M. R., Mitchell, J. F. B. and Jenkins, G. J.: External Control of 20th Century Temperature by Natural and Anthropogenic Forcings, Science, 290(5499), 2133–2137, doi:10.1126/science.290.5499.2133, 2000.

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

UGRH: Plano batymétrico de la laguna Palcacocha, Autoridad Nacional del Agua (ANA), Unidad de Glaciología y Recursos Hídricos (UGRH), Huaraz, Perú., 2016.

UNISDR: Terminology on disaster risk reduction, United Nations International Strategy for Disaster Reduction UNISDR, Geneva., 2009.

Vilimek, V., Zapata, M. L., Klimeš, J., Patzelt, Z. and Santillán, N.: Influence of glacial retreat on natural hazards of the Palcacocha Lake area, Peru, Landslides, 2(2), 107–115, 2005.

Vuille, M., Francou, B., Wagnon, P., Juen, I., Kaser, G., Mark, B. G. and Bradley, R. S.: Climate change and tropical Andean glaciers: Past, present and future, Earth Sci. Rev., 89(3–4), 79–96, 2008.

Vuille, M., Franquist, E., Garreaud, R., Lavado Casimiro, W. S. and Cáceres, B.: Impact of the global warming hiatus on Andean temperature, J. Geophys. Res. Atmospheres, 120(9), 2015JD023126, doi:10.1002/2015JD023126, 2015.

Wallimann-Helmer, I.: Differentiating responsibilities for climate change adaptation, Arch. Für Rechts- Sozialphilosophie, Beihefte 149, 119–132, 2016.

Wallimann-Helmer, I.: Common but differentiated responsibilities: agency in climate justice, in A Research Agenda for Climate Justice, edited by P. Harris, pp. 27–37, Edward Elgar Publishing, Camberley Surey. [online] Available from: https://www.e-elgar.com/shop/a-research-agenda-for-climate-justice, 2019.

Wallimann-Helmer, I., Meyer, L., Mintz-Woo, K., Schinko, T. and Serdeczny, O.: The Ethical Challenges in the Context of Climate Loss and Damage, in Loss and Damage from Climate Change: Concepts, Methods and Policy Options, edited by R. Mechler, L. M. Bouwer, T. Schinko, S. Surminski, and J. Linnerooth-Bayer, pp. 39–62, Springer International Publishing, Cham., 2019.

Walton, N. K.: Human Spatial Organization in an Andean Valley: The Callejón de Huaylas, Ph.D., University of Georgia, Athens., 1974.

Warner, K. and van der Geest, K.: Loss and damage from climate change: local-level evidence from nine vulnerable countries, Int. J. Glob. Warm., 5(4), 367–386, doi:10.1504/IJGW.2013.057289, 2013.

Wegner, S. A.: Lo que el agua se llevó. Consecuencias y lecciones del aluvión de Huaraz de 1941, Notas Técnicas sobre Cambio Climático, 7, Huaraz, Peru., 2014.

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., p. 241, Routledge, New York., 2015.

Wisner, B., Blaikie, P. M., Cannon, T. and Davis, I.: At risk: natural hazards, people’s vulnerability and disasters, Routledge, London., 2004.

Wrathall, D. J., Bury, J., Carey, M., Mark, B. G., McKenzie, J., Young, K., Baraer, M., French, A. and Rampini, C.: Migration Amidst Climate Rigidity Traps: Resource Politics and Social–Ecological Possibilism in Honduras and Peru, Ann. Assoc. Am. Geogr., 104, 292–304, 2014.

Yauri Montero, M.: Ancash o la bigrafía de la inmortalidad: Nuevo planteamiento de sus problemas culturales, P.L. Villanueva S.A., Lima., 1972.

Yauri Montero, M.: Leyendas ancashinas, Sexta Edición., Lerma Gómez eirl., Lima., 2000.

Zapata, M. L., Gómez, R. J., Cochachin, A., Santillán, N., Montalvo, C. and Lizarme, G.: Memoria anual 2003, INRENA, Huaraz, Perú., 2004.

Zemp, M., Frey, H., Gärtner-Roer, I., Nussbaumer, S. U., Hoelzle, M., Paul, F., Haeberli, W., Denzinger, F., Ahlstrøm, A. P., Anderson, B., Bajracharya, S., Baroni, C., Braun, L. N., Cáceres, B. E., Casassa, G., Cobos, G., Dávila, L. R., Delgado Granados, H., Demuth, M. N., Espizua, L., Fischer, A., Fujita, K., Gadek, B., Ghazanfar, A., Hagen, J. O., Holmlund, P., Karimi, N., Li, Z., Pelto, M., Pitte, P., Popovnin, V. V., Portocarrero, C. A., Prinz, R., Sangewar, C. V., Severskiy, I., Sigurðsson, O., Soruco, A., Usubaliev, R. and Vincent, C.: Historically unprecedented global glacier decline in the early 21st century, J. Glaciol., 61(228), 745–762, doi:10.3189/2015JoG15J017, 2015.

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 $0.515 \cdot 10^6$ 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 $3.690 \cdot 10^6$ m^3	(Zapata et al., 2004)
2003 - present	Accelerated lake growth	See main text	(UGRH, 2016)
2009	Bathymetry	Volume $17.325 \cdot 10^6$ 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 $17.403 \cdot 10^6$ m^3	UGRH, 2016
August 2018	Remediation	Lake level lowered by 3 m	Field visits

Table 1: Milestones in the evolution of Lake Palcacocha.

Figures

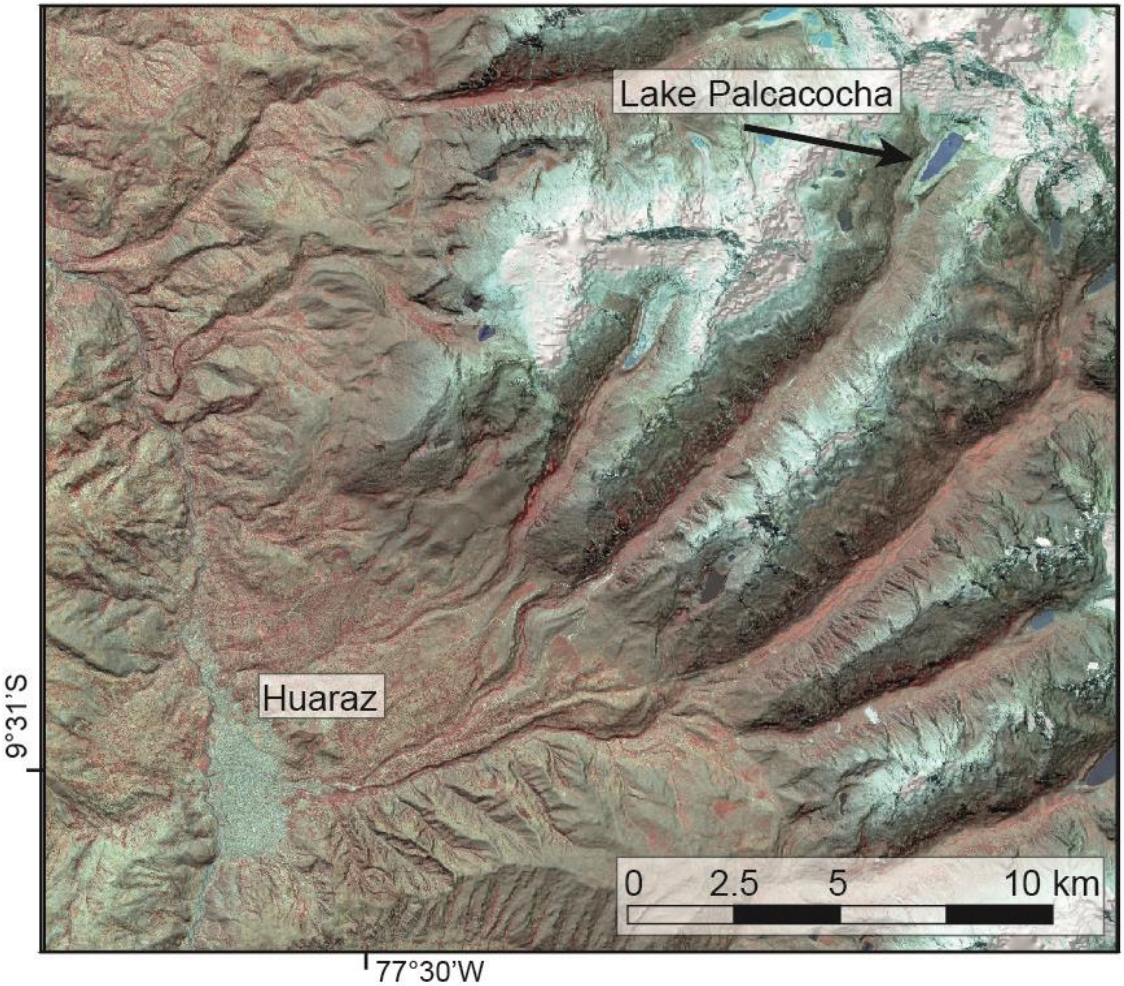

Figure 1: Study region with Lake Palcacocha and the city of Huaraz (source SPOT image, year of acquisition: 2006).

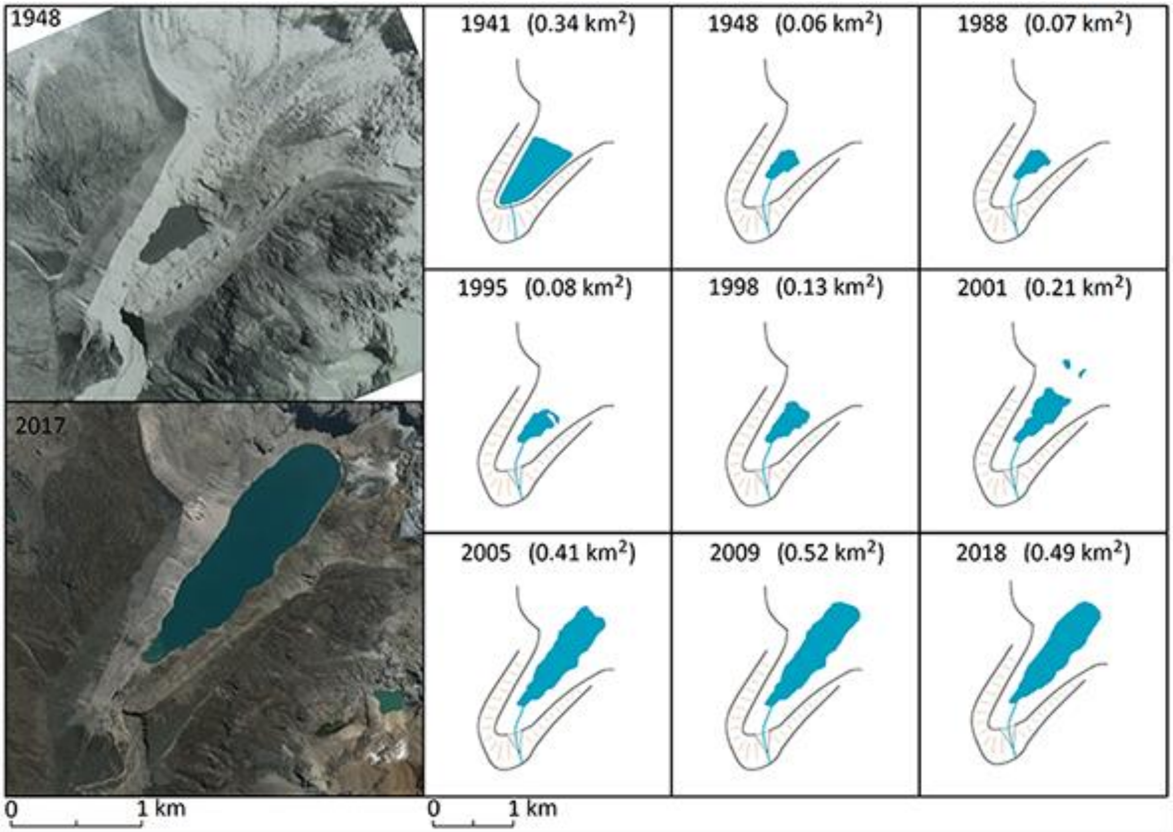

Figure 2: Evolution of Lake Palcacocha from 1941 to present (source of 1948 image: Archives of the Autoridad Nacional de Agua, Peru, source of 2017 image: CNES/Airbus image, Google Earth, date of acquisition: 18 June 2017, source of lake evolution 1988-2018: Landsat images).

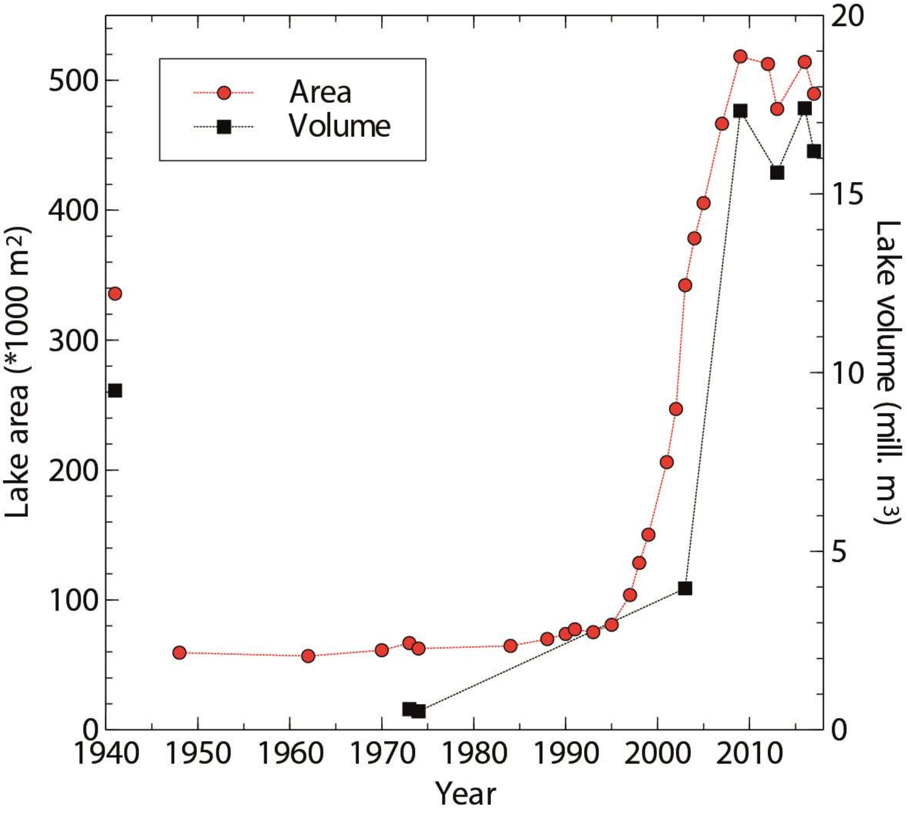

Figure 3: Evolution of area and volume of lake Palcacocha 1941 to present (data sources: see Table 1).

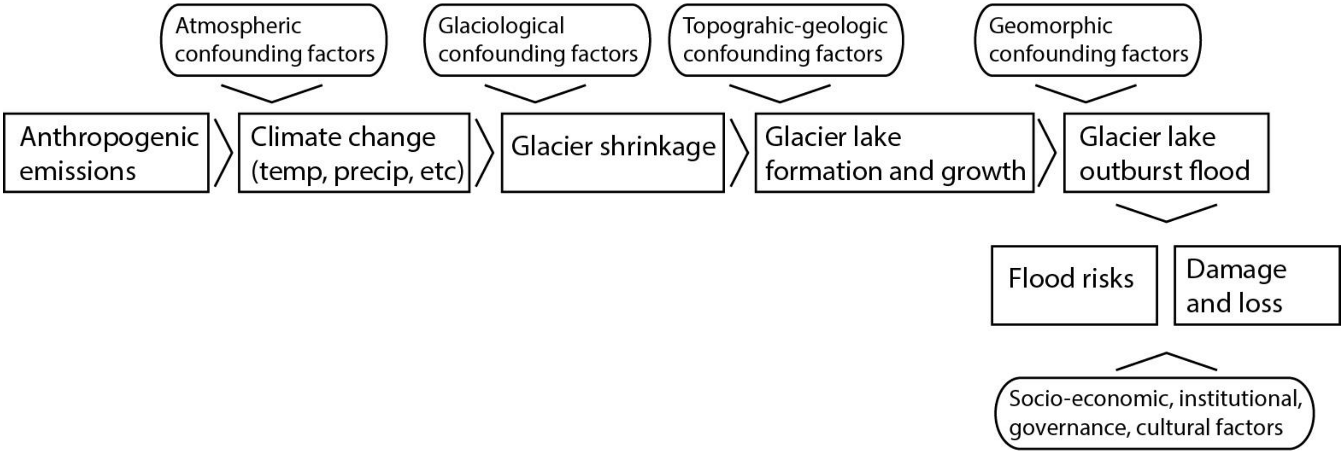

Figure 4: Causation chain from anthropogenic emissions to glacier lake flood risk. At each element of the causation chain non-climatic (confounding) factors are indicated which also influence the respective element.

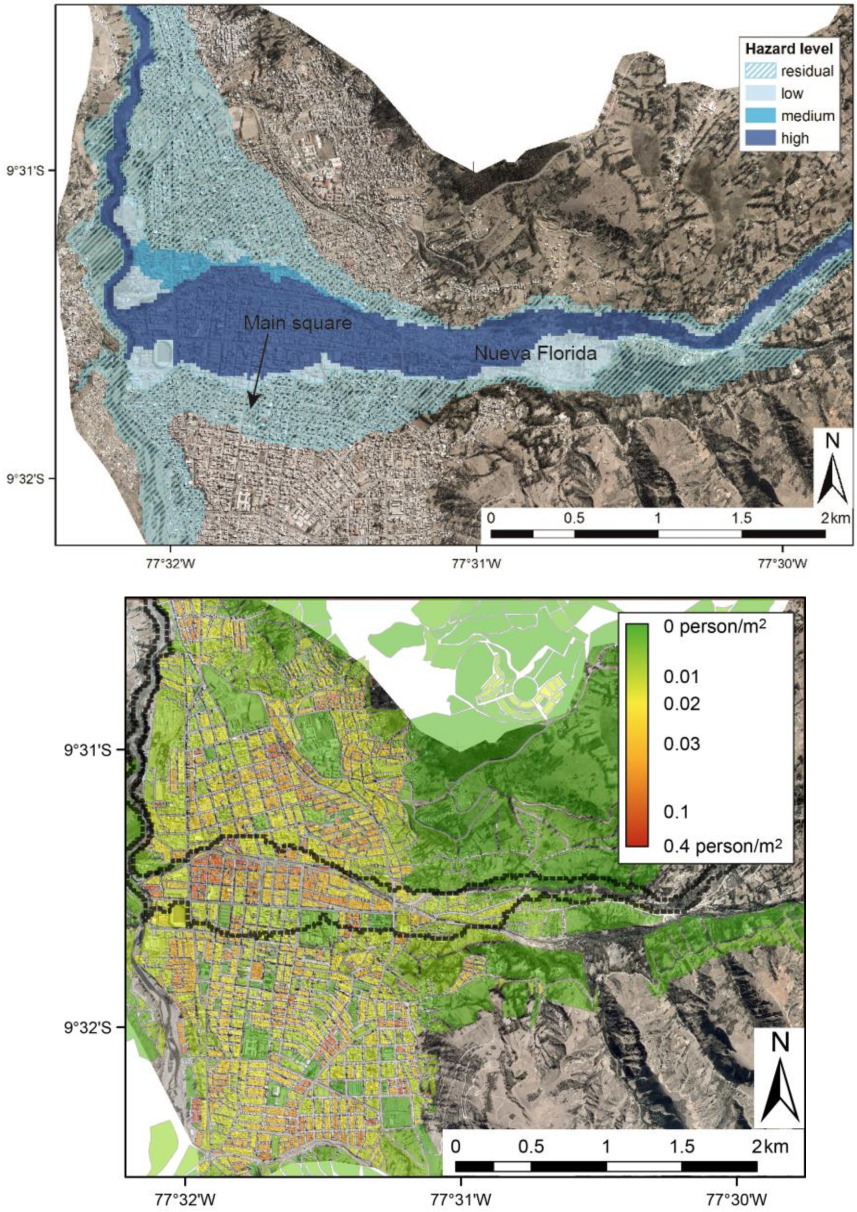

Figure 5: Top panel: Hazard map for the city of Huaraz as related to GLOFs from Lake Palcacocha. The district of Nueva Florida and the main square of the city are indicated (for a more detailed description of the hazard mapping methodology see supplementary material) (source of image: Google Earth / 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: INEI).

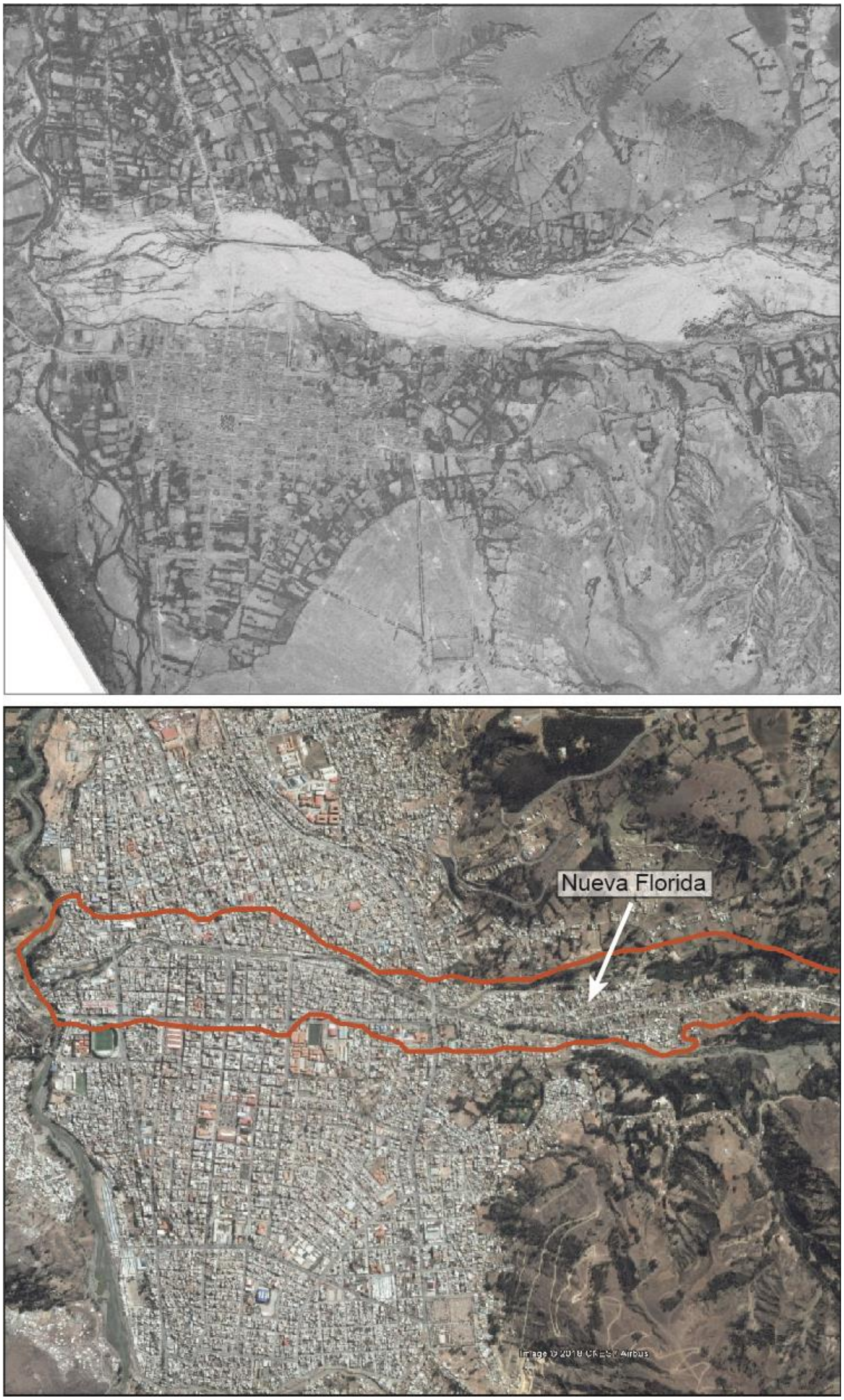

Figure 6: Aerial photograph from 1948 showing the traces of the 1941 GLOF (upper panel), and 2016 satellite image of the same area (lower panel). The outlines in orange indicate the extent of the area affected by the 1941 GLOF. The

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).

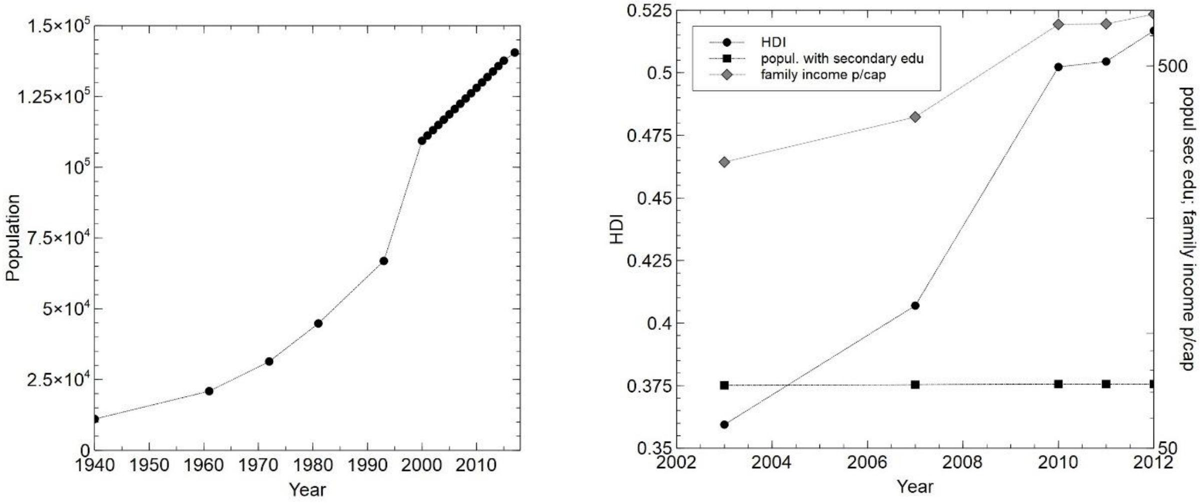

Figure 7: Population growth of Huaraz over the period 1941-2017. Data since the year 2000 is based on an extrapolation produced by the National Statistical Office of Peru (INEI) (left panel). Vulnerability indicators and their changes between 2002 and 2012 for the city of Huaraz. HDI: human development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