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An integrated socio-environmental framework for glacier hazard management and climate change adaptation: lessons from Lake 513, Cordillera Blanca, Peru

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Abstract Glacier hazards threaten societies in mountain regions worldwide. Glacial lake outburst floods (GLOFs) pose risks to exposed and vulnerable populations and can be linked in part to long-term post-Little Ice Age climate change because precariously dammed glacial lakes sometimes formed as glaciers generally retreated after the mid-1800s. This paper provides an interdisciplinary and historical analysis of 40 years of glacier hazard management on Mount Hualcán, at glacial Lake 513, and in the city of Carhuaz in Peru's Cordillera Blanca mountain range. The case study examines attempted hazard zoning, glacial lake evolution and monitoring, and emergency engineering projects to drain Lake 513. It also analyzes the 11 April 2010 Hualcán rock-ice avalanche that triggered a Lake 513 GLOF; we offer both a scientific assessment of the possible role of temperature on slope stability and a GIS spatial analysis of human impacts. Qualitative historical analysis of glacier hazard management since 1970 allows us to identify and explain why certain actions and policies to reduce risk were implemented or omitted. We extrapolate these case-specific variables to generate a broader socio-environmental framework identifying factors that can facilitate or impede disaster risk reduction and climate change adaptation. Facilitating factors are technical capacity, disaster events with visible hazards, institutional support, committed individuals, and international involvement. Impediments include divergent risk perceptions, imposed government policies, institutional instability, knowledge disparities, and invisible hazards. This framework emerges from an empirical analysis of a coupled social-ecological system and offers a holistic approach for integrating disaster risk reduction and climate change adaptation.

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1 Introduction

Scholars are increasingly calling for more studies that analyze the practices and processes of climate change adaptation (Arnell 2010; Pfister 2010). Empirically grounded research on actual cases of climate change adaptation would complement existing scholarship on hypothetical scenarios, future projections, and theories of adaptive capacity. It would also help illuminate how and why effective adaptation takes place (or doesn't), what facilitates or obstructs the implementation of adaptive measures, and who participates (or doesn't) in such processes. Climate change adaptation strategies and policies could also be improved through a more rigorous connection with disaster risk reduction agendas—thereby producing more holistic or integrated approaches to both hazard management and climate change adaptation (Birkmann, Tetzlaff, and Zentel 2009; Birkmann and Teichman 2010; Mercer 2010; Thomalla et al. 2006). Recognizing the connection between climate change and natural hazards, Working Group II of the Intergovernmental Panel on Climate Change (IPCC) is currently preparing a special report on "Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX)." A preliminary SREX report (Barros et al. 2009) suggests that, although disaster events can be difficult to attribute to climate due to interaction of climate with other environmental and socio-economic factors, it is nonetheless expected that unpredictable extreme weather events are likely to increase in intensity and frequency. Moreover, disaster risk reduction strategies have been well developed and refined for much longer than climate change adaptation agendas have existed; thus the tools, methods, and policies used for disaster risk reduction can enhance climate change adaptation strategies over the short and long term (Barros et al. 2009). To refine and improve both disaster prevention and climate change adaptation, it is important to draw lessons from actual cases of disaster risk reduction—especially those cases when climate change influenced the evolution of natural hazards, as this paper examines (Amendola et al. 2008; McEntire et al. 2002).

To be most effective, these studies on actual practices of disaster risk reduction and climate change adaptation must be inter-disciplinary to recognize and analyze dynamic social-ecological systems (SESs) or coupled human-environment systems (Folke 2006; Turner et al. 2003; Young et al. 2006). Human vulnerability, perceptions, responses, and decision-making processes must be integrated with scientific assessments, technological innovations, and engineering strategies associated with hazard management (Rosenzweig and Wilbanks 2010; Smit and Wandel 2006). Moreover, as disaster research and planning has long recognized, there is no such thing as a "natural" disaster, only natural hazards; disasters are socio-economic and political because they involve people (Maskrey 1993; Wisner et al. 2004). Risk, then, is defined by the combination of three elements: (1) the likelihood of a physical event occurring (the natural hazard); (2) the degree of human exposure; and (3) the level of human vulnerability (Barros et al. 2009; Thierry et al. 2008; Wisner et al. 2004). These combined societal and environmental elements cannot be easily disentangled, and thus effective disaster risk reduction and climate change adaptation agendas require holistic, interdisciplinary approaches.

The need to integrate climate change adaptation with disaster risk reduction is particularly important in glaciated mountain regions, which are among the world's most sensitive and vulnerable areas to climate change (Beniston 2003; Gardner and Dekens 2007; Rosenzweig et al. 2007). Climate has a significant influence on the mass balance of mountain glaciers, and the IPCC reports with "high confidence" that warming has led both to a reduction in snow and ice masses and to the formation of moraine-dammed glacial lakes that can “have a high potential for glacial lake outburst floods (GLOFs)” (Rosenzweig et al. 2007: p. 86). In glaciated mountains and watersheds, climate change—acting in combination with other environmental and societal factors—has already caused notable, in some cases catastrophic, consequences as glaciers retreat (Carey 2010; Clague and Evans 2000; Haeberli et al. 1989; Kääb et al. 2007; Kääb et al. 2005b; Richardson and Reynolds 2000). In particular, unstable moraine-dammed glacial lakes have formed in sites where retreating glacier tongues created flat or overdeepened spaces for lakes to form behind moraines (Ames 1998; Zapata Luyo 2002). The GLOF risk emerges not only when the lake forms behind such unstable moraine dams, but also when there are exposed and vulnerable human populations inhabiting valleys below these glacial lakes. Other glacier-related hazards such as destabilization of steep glaciers and rock slopes can occur in relation with increasing temperatures in firn and ice, permafrost thaw or debuttressing effects due to retreating glaciers (O’Connor and Costa 1993; Huggel 2009). Such rock and ice avalanches from slope failures are particularly relevant with respect to glacial lakes because they can generate displacement waves in the lakes and trigger GLOFs (Kershaw et al. 2005; Haeberli and Hohmann 2008).

Research on glacier hazards has expanded into many areas in recent years, including the identification and description of past glacier disaster events (Clague and Evans 2000; Ghimire 2005; Haeberli et al. 1989; Kääb et al. 2005b; Narama et al. 2010; Richardson and Reynolds 2000), hazard assessment (Huggel et al. 2004; Kääb et al. 2005a; Watanabe et al. 2009; Werder et al. 2010), mitigation (Grabs and Hanisch 1993; Haeberli et al. 2001; Huggel et al. 2008; Reynolds 1993), perceptions (Carey 2007; Cruikshank 2005; Jurt 2009; Orlove et al. 2008), vulnerability (Hegglin and Huggel 2008), impacts (Bury et al. 2011; Carey 2010; Young and Lipton 2006), and adaptation (Carey 2005; Kattelmann 2003; Orlove 2009). The vast majority of this research has been conducted by environmental scientists in the areas of hazard identification and assessment. Social scientists, however, are also increasingly studying glacier hazards in various world regions. Nevertheless, the integration of the social and environmental sciences in climate change and natural disaster research has barely occurred for the analysis of glacier hazards.

This paper provides such an integrated, interdisciplinary socio-environmental study of glacier hazard management in Peru, with broader implications for disaster risk reduction and climate change adaptation beyond the Andes. We call this a socio-environmental framework because the more commonly used concepts of socio-ecological or social-ecological systems (Folke et al. 2005; Young et al. 2006) tend to emphasize ecosystems, natural resources, and biophysical processes, thereby inadvertently de-emphasizing geophysical processes. The term “environmental” instead of “ecological” suggests a broader concept that encompasses biological systems, climate, hydrology, and the cryosphere. Our framework presented in the second part of this paper emerges from an analysis of long-term GLOF prevention strategies at Lake 513 in the Cordillera Blanca, Peru—the empirical case study that we present in the first part. On 11 April 2010, a rock-ice avalanche from Mount Hualcán crashed into Lake 513 and generated a GLOF that destroyed property and infrastructure near the city of Carhuaz. This event was a surprise to local residents, policy makers, scientists, and engineers because Lake 513 had been partially drained during the 1980s and 1990s. Experts had thereafter classified the lake as “secure,” with a low GLOF threat prior to the April 2010 event. Carhuaz had also been the site for a hazard zoning program during the 1970s, when government officials tried to reduce human exposure to potential glacier avalanches and GLOFs. The area has thus undergone more than 40 years of comprehensive glacier hazard management that involved various policies and engineering strategies to reduce the risk of glacier-related disasters.

Given that the IPCC (Adger et al. 2007; Rosenzweig et al. 2007) links glacier shrinkage, glacial lake formation, and GLOF threats to climate change, the case of Lake 513 is also an example of long-term climate change adaptation—even though historical actors and stakeholders emphasized glaciers, not climate, as the culprit, even though climate never acted alone in creating either the hazard or the societal risk, and even though we make no claims about whether the Lake 513 hazard can be attributed to anthropogenic climate change.

The long-term successful efforts to drain Lake 513 and reduce the GLOF risk, on the one hand, combined with the development of an unidentified threat above exposed people, property, and infrastructure, on the other hand, makes this an excellent case to empirically study and qualitatively identify the drivers and controls that facilitated and impeded successful disaster risk reduction and climate change adaptation over time. Our ground-level empirical analysis demonstrates that disaster risk reduction and adaptation to climate change are not one-time occurrences. Instead, they require ongoing and continual adjustments, the acquisition of new knowledge, evaluation, monitoring, mitigation, public education, preparedness, and open dialogue among various stakeholders and decision makers.

2 Terminology

The United Nations International Strategy for Disaster Reduction (UNISDR) defines disaster risk reduction as "the concept and practice of reducing disaster risks through systematic efforts to analyze and reduce the causal factors of disasters. Reducing exposure to hazards, lessening vulnerability of people and property, wise management of land and the environment, and improving preparedness for adverse events are all examples of disaster risk reduction" (www.unisdr.org). UNISDR recognizes that there are "natural hazards" such as earthquakes or droughts, but maintains that all disasters are social and political rather than "natural" (also see Maskrey 1993; Wisner et al. 2004). The IPCC defines climate change adaptation as "actual adjustments, or changes in decision environments, which might ultimately enhance resilience or reduce vulnerability to observed or expected changes in climate and associated extreme weather events" (Adger et al. 2007: p. 720). There are many similarities between initiatives to reduce risk and adapt to climate change (Mercer 2010), and both strategies target integrated socio-environmental systems while focusing on minimizing the societal impact of environmental change and natural hazards. Bridging disaster risk reduction and climate change adaptation is particularly appropriate for glacier hazards, and the IPCC Working Group II recognizes that adaptive measures are "being put into place in developing country contexts to respond to glacier retreat and associated risks, such as the expansion of glacial lakes, which pose serious risks to livelihoods and infrastructure" (Adger et al. 2007: p. 721).

To date, however, there is a dearth of interdisciplinary studies that analyze the variables that either facilitated or impeded the implementation of such measures to reduce the risk of GLOFs and thus help adapt to climate-related environmental change in specific socio-economic and political contexts. This paper provides such an interdisciplinary study of glacier hazard management. We define integrated "glacier hazard management" as measures that reduce the risk of glacier-related disasters. These measures could involve the prediction of glacier hazards, the drainage or containment of glacial lakes to remove the possibility of a GLOF, the minimization of the portion of the population exposed to glacier hazards, and the reduction of human vulnerability. These various aspects of glacier hazard management follow the UNISDR, IPCC, and other scholarship on disaster risk reduction and climate change adaptation that recommend multi-level and integrated socio-environmental approaches (e.g. Adger et al. 2007; Thierry et al. 2008; Wisner et al. 2004).

It should also be noted that this paper does not analyze whether glacier hazards are caused by anthropogenic climate change because this is beyond the paper's scope. When we refer to "climate change," we do *not* mean anthropogenic climate change, but rather just changes in the climate system, whatever the cause. Climate change adaptation can and historically has occurred even when it is not attributed to anthropogenic climate change. Moreover, the link between anthropogenic climate change and disasters remains inconclusive (Bouwer 2011). Glacier hazards in the Cordillera Blanca have existed for decades and centuries, and the most destructive and deadly GLOFs for regional inhabitants occurred between 1941 and 1950, in response to glacier retreat that began in the late-nineteenth century (Ames 1998; Zapata Luyo 2002). Scientists have recognized the role of climate on glacier retreat and GLOF threats in the Cordillera Blanca since at least 1940 (e.g. Kinzl 1940; Broggi 1943), but it was not identified as anthropogenic climate change. In fact, while century-scale glacier retreat in the Peruvian Andes has been related to climate change (Magrin et al. 2007; Rosenzweig et al. 2007), the exact climate-glacier processes driving glacier shrinkage are not yet fully understood. Temperature-precipitation feedbacks and humidity are important drivers of glacier mass balance in the Cordillera Blanca, and on interannual time-scales sea surface temperature anomalies in the tropical Pacific and ENSO exert important forcing (Kaser 2001; Vuille et al. 2008a). Relevant to this paper is that climate change, whether natural or anthropogenic, is closely linked to long-term glacier retreat, and thus to the formation of glacial lakes. The link between climate change and high-mountain slope stability is more complicated, however, as climate is only one among several other factors controlling slope stability. It is understood that atmospheric warming causes permafrost thaw and an increase of firn and ice temperature on steep glaciers, decreasing slope stability (Gruber and Haeberli 2007; Huggel 2009). However, clearly attributing a particular high-mountain slope failure to impacts of climate change is hardly possible, even with advanced mechanical slope stability modeling (Fischer et al. 2010). Nevertheless, studies have found an increase of high-mountain slope failures in recent decades and established links to contemporaneous warming (Allen et al. 2010; Ravanel and Deline 2011). However, a detailed attribution study, either for the slope failure or the outburst flood at Lake 513, is beyond the scope of this paper.

3 Methodology

This paper has two major sections: a case study of glacier hazard management at Peru's Lake 513 and a socio-environmental framework drawn from analysis of the case study that identifies the most significant variables that facilitated or obstructed successful glacier hazard management. The empirical case study presented in Section 4 has three subcomponents. First, it involves a historical analysis of glacier hazard management from 1970 to 2010. This environmental history and science and technology studies (STS) research involved the analysis of hundreds of documents (technical reports, newspaper articles, testimonies, government reports, and legal documents), oral histories, and published secondary sources to understand local perceptions and responses to hazards, government policies, scientific and engineering recommendations, and the evolution of glacier hazard management over time and within its relevant technical, political, economic, and social contexts. It also involved an examination of published and unpublished technical studies in order describe the changing physical environment on Mount Hualcán and at Lake 513 and the evolution of engineering strategies developed to reduce the GLOF threats. Second, the paper describes and analyzes the 11 April 2010 Mount Hualcán avalanche and ensuing Lake 513 GLOF. Field surveys have been undertaken at Lake 513 and along the flood path of the GLOF days and weeks after the event, allowing us to reconstruct in detail the rock-ice avalanche, its impact on Lake 513, and the resulting flood. Topographic maps, high-resolution satellite images (see below) and repeated photographs were used to analyze the conditions of the Hualcán flank and Lake 513. For thermal aspects of the slope failure data from several meteorological stations of the region were investigated. Third, the 2010 event is also analyzed to understand the human impacts. To evaluate these effects, a mixed set of methods were utilized that included analyses of recent government reports and media coverage, key interviews with government and civil society representatives in July 2010, and unstructured interviews with 10 households affected by the event . In addition, a pre- and post-impact GIS spatial analysis was conducted of the entire affected area utilizing high resolution satellite imagery (Digitalglobe Worldview imagery, ~50 cm-June 1, 2010; June 2, 2005), moderate resolution imagery (ASTER imagery, ~30 m-June 23, 2010; May 15, 2009), Peruvian national mapping data and land parcel data from the Peruvian Special Land Titling and Rural Cadastral Project (PETT).

The socio-environmental framework presented in Section 5 is a qualitative interdisciplinary analysis of the empirical case study. We identified certain factors that helped reduce the risk of glacier hazards, and we assumed that the ideal or most successful form of glacier hazard management would be to reduce risk to zero. We analyzed the historical documents mentioned above and the recent socio-environmental aspects of the 2010 GLOF to understand why certain decisions were made or challenged, why policies were created or resisted, and why projects were implemented or not. We identify and present these factors that influenced decisions, policies, and projects as a framework so that the variables can be tested on other sites where disaster risk reduction and climate change adaptation have or may take place.

4 Cordillera Blanca case study

The Cordillera Blanca runs approximately 180 km north–south in central Peru (see Fig. 1). It contains more than 60 mountains above 5700 m, with Mount Huascarán (6,768 m) the highest in the country. The glacierized area of the range in 2003 was estimated at ~569 km^2, and it accounts for approximately 25 % of the world's tropical ice, making the Cordillera Blanca the most glaciated mountain range in the tropical world (Casassa et al. 2007; Georges 2004; Racoviteanu et al. 2008; Vuille, et al. 2008a). To the west of the Cordillera Blanca is the Cordillera Negra mountain range—and between these two ranges lies the Santa River Valley, known in Peru as the Callejón de Huaylas. The Santa River runs through the bottom of this valley and turns west at Cañón del Pato, cutting through the Cordillera Negra before descending to the coastal plain and flowing into the Pacific Ocean just north of the port city of Chimbote. The Callejón de Huaylas has many towns and cities along the Santa River, including the Ancash capital city of Huaraz (pop. 96,000) and others such as Caraz (13,000), Carhuaz (7,200), and Yungay (8,000) (Fig. 1). Approximately 267,000 people inhabit the Callejón de Huaylas, with a much larger population in proximity of the Cordillera Blanca on the eastern slopes and in the lowland Santa River valley (INEI 2007; Mark et al. 2010). Most Callejón de Huaylas towns and cities are located along the Santa River, where Spaniards settled in the sixteenth century. The

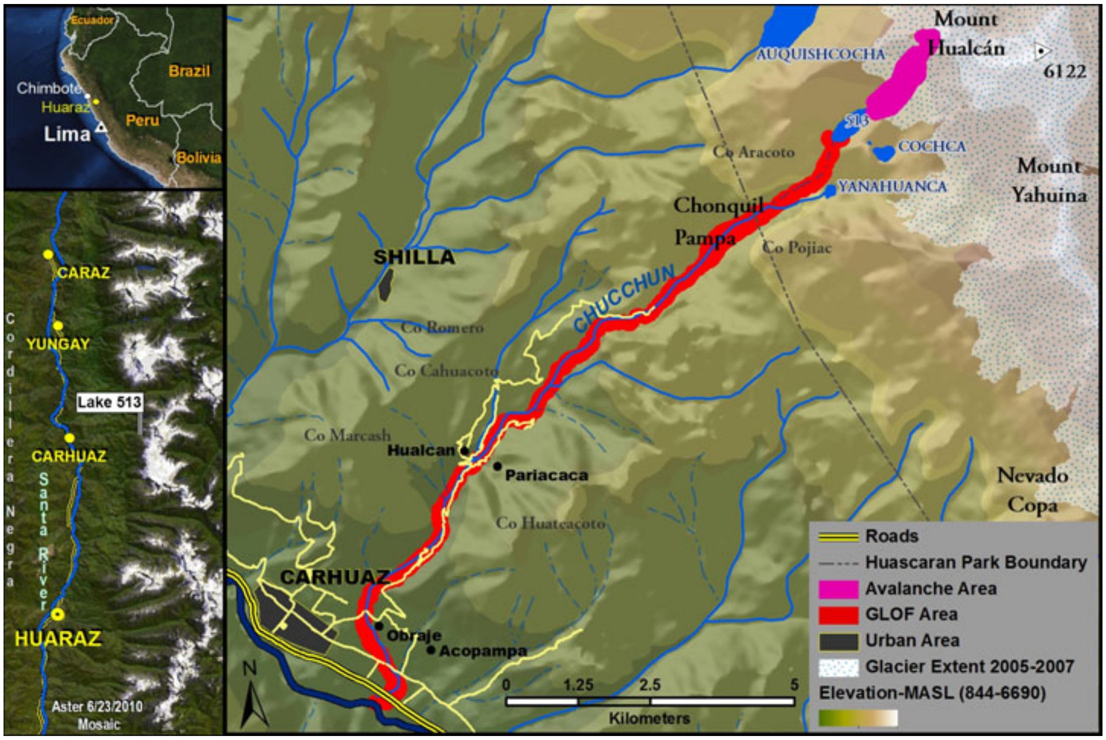

Fig. 1 Cordillera Blanca, Callejón de Huaylas, Santa River, Carhuaz, Mount Hualcán, and Lake 513, with avalanche path and flooded area highlighted

rural upland population, usually categorized as more indigenous because of its Quechua heritage, consists primarily of subsistence farmers and pastoralists. Class and race divisions that date to Peru's colonial era continue to divide segments of the population, especially urban from rural, white and *mestizo* (mixed race) from indigenous, wealthy from poor, lowland from highland, and coastal from sierra. Although Peruvians generally refer to these rigid race and class divisions, the categories of course are not so distinct in practice (de la Cadena 2000).

The Cordillera Blanca has produced some of the world's most deadly glacier disasters, and the urban areas, including Carhuaz, on the banks of the Santa River and its tributaries have been the most exposed to GLOFs and glacier avalanches. A 1941 GLOF killed 5,000 people and destroyed a third of the Ancash capital city of Huaraz. Two more GLOFs in 1945 and 1950 caused nearly 1,000 deaths and destroyed ancient ruins at Chavín de Huantar and a nearly completed hydroelectric station at Cañón del Pato on the Santa River (Carey 2010). These catastrophic GLOFs—as well as many others that were less destructive, including two at Lake 513—occurred because moraine-dammed lakes formed when glacier tongues retreated after the end of the Little Ice Age (LIA) in the mid-nineteenth century. Despite some brief periods of glacier advances in the mid-1920s, late 1970s, and 1990s, there has been an overall trend of Cordillera Blanca glacier retreat and loss of ice volume since the LIA ended: the glacierized area declined from approximately 850–900 km^2 during the LIA to less than 600 km^2 at the end of the twentieth century (Georges 2004; Racoviteanu et al. 2008; Silverio and Jaquet 2005; Vuille et al. 2008b). This trend of glacier retreat has occurred in parallel with climate change, even though the attribution of glacier shrinkage to a specific climate forcing requires more research. Attribution is complicated both because glaciers are sensitive to numerous climate forcings such as temperature, precipitation, and humidity and because tropical glaciers behave differently than the more thoroughly studied mid- and high-latitude glaciers (Kaser and Osmaston 2002; Vuille et al. 2008b). As Cordillera Blanca glaciers retreated since the end of the LIA, dozens of precariously dammed lakes formed and expanded behind unstable moraine dams. The steadily growing number and size of glacial lakes perched precariously above exposed Callejón de Huaylas populations inhabiting potential flood paths thus increased the risk of GLOFs (Ames 1998; Carey 2010; Fernández Concha 1957; Kinzl 1940; Lliboutry et al. 1977; Zapata Luyo 2002). As early as the 1940s—which was many decades before any international discussion of anthropogenic climate change—scientists recognized that climate played a critical role in the development of these Cordillera Blanca GLOF hazards (Kinzl 1940; Broggi 1943; Oberti 1973). Not all Cordillera Blanca glacier hazards were climate related, however. The most deadly glacier disaster was the 1970 avalanche that killed an estimated 6,000 people and buried the city of Yungay (previous reports estimated 15,000 deaths); the avalanche was triggered by a massive earthquake that killed 55,000 people beyond the avalanche victims and left hundreds of thousands homeless (Bode 1990; Ericksen et al. 1970; Evans et al. 2009; Oliver-Smith 1986).

After the 1950 Los Cedros GLOF destroyed the Cañón del Pato hydroelectric station, the Peruvian government established a still-ongoing GLOF prevention program that involved extensive glacier and glacial lake monitoring and engineering projects to partially drain and dam 34 Cordillera Blanca lakes (Ames 1998; Ames Marquez and Francou 1995; Carey 2005, 2010; Lliboutry et al. 1977; Portocarrero 1995; Zapata Luyo 2002). The Lakes Commission created in 1951 has undergone many administrative changes since then, but it has continued its glacial hazard investigations, Cordillera Blanca monitoring, innovative engineering projects, and disaster prevention programs ever since. The institution is currently called the Glaciology and Hydrological Resources Unit (UGRH: Unidad de Glaciología y Recursos Hídricos). The region's tragic history with glacier hazards, coupled with its many successful and ongoing programs to prevent GLOFs that stem in part from climate change, make it an ideal site for studying an actual case of integrated disaster risk reduction and climate change adaption.

4.1 Mount Hualcán hazard identification in the 1970s

Glacier hazards on Mount Hualcán and for the city of Carhuaz were first identified in the late 1960s, when mountaineers noticed a glacier fissure 500 m long on the mountain. They reported in Lima's *El Comercio* on 19 July 1967 that the glacier was on the verge of breaking apart and causing a catastrophic avalanche that would crash into Lake Cochca or Lake Yanahuanca and trigger a GLOF. The first systematic studies of Hualcán glaciers, however, did not occur until after the 1970 Mount Huascarán avalanche. A UNESCO delegation led by French glaciologist Louis Lliboutry concluded that glaciers and glacial lakes throughout the Cordillera Blanca were unstable (Lliboutry et al. 1970). The report noted specifically that Mount Hualcán could potentially produce both ice-rock avalanches and GLOFs, especially if avalanches reached glacial lakes—the same process that triggered the 11 April 2010 GLOF. To protect Carhuaz residents in 1970, the UNESCO delegation proposed draining glacial Lake Cochca and relocating local populations outside the floodplain. Government officials and experts proposed Huáchac as the new site for Carhuaz because, as they explained to the public on 12 November 1970 in *El Comercio*, it was recognized as safe from both glacier avalanches and GLOFs.

In 1972, the Peruvian Division of Glaciology and Lake Security, a precursor to today's UGRH, conducted its own glaciological studies of Mount Hualcán glaciers. Peruvian engineers concluded that both rock and ice avalanches had previously occurred in the region and could occur again in the future (División de Glaciología y Seguridad de Lagunas 1972; Oberti 1973). Glacier 513a was recognized as particularly unstable at that time because its glacier tongue was covered with a large amount of debris, indicating frequent snow and ice avalanches. If an avalanche reached Lake Cochca, which at the time held 900,000 m^3 of water, a combined avalanche-outburst flood could reach 4.8 million m^3, enough to inundate thousands in Carhuaz (Oberti 1973). Several mechanisms were identified that could trigger the event: long term climate change, successive accumulation of snow and ice, significant temperature variation within a single day, or an earthquake. Peru's glaciology office lacked adequate resources, however, to study and monitor these climatic, geologic, and glacial conditions. Nor was there a mechanism in place to provide advance warning to residents in potential avalanche and flood paths below. The Glaciology Division reiterated the need to relocate exposed areas of Carhuaz along the Chucchun River to a safer site. Because the 1970 earthquake had destroyed many homes, buildings, roads, and other infrastructure that were still not entirely reconstructed, relocation did not entail moving intact communities.

Local residents, however, rejected the proposed zoning laws, not only in Carhuaz but throughout the Callejón de Huaylas. They resisted relocation plans designed to advance long-term glacier hazard management because perceived political, social, and economic risks overshadowed their perception of climatic or glacier hazards. Other studies explain these reasons in detail (e.g. Bode 1977, 1990; Carey 2008, 2010; Oliver-Smith 1977, 1982, 1986). By opposing relocation plans, Carhuaz residents became exposed to subsequent glacier hazards when a new glacial lake formed at the base of Glacier 513a in the early 1980s. They thus obstructed ideal disaster risk reduction and climate change adaptation programs because, as elaborated below, they remained exposed and vulnerable to hazards that developed when the Glacier 513a tongue retreated and created a space for a new glacial lake to form behind a precariously dammed ice-cored moraine.

4.2 GLOF prevention at Lake 513

The new Lake 513 on Mount Hualcán was first noticed as a rapidly growing, dangerous glacial lake by the UGRH during routine Cordillera Blanca monitoring in 1980. Another UGRH investigation in 1985 revealed that, as a result of considerable glacier retreat, the Glacier 513a tongue had largely detached from the active glacier (HIDRANDINA 1990). Its dead ice body filled a basin approximately 250 m wide and 750 m long. A glacial lake 120 m deep had formed in the basin and was dammed mostly by solid bedrock except for the most crucial upper lake level, which was dammed by a 15 m high ice-cored terminal moraine that rested on top of the bedrock. By August 1988, the lake volume had grown to 1.5 million m^3 of water, which was estimated to be enough to inundate Carhuaz. The lake's moraine dam had also slumped 4 m between 1985 and 1988 (at a rate of 1.3 m per year or 11 cm per month) as its dead ice core melted. During those same three years, the lake depth had increased by 10 m. The freeboard in 1988 was less than 1 m as a result of the simultaneous sinking dam and rising lake level. Lake 513 was also draining both through filtration through the moraine and through two springs that had formed below the moraine. Moreover, a wall of ice 1,700 m high rose directly above the lake, and it generated daily avalanches that threatened to destabilize Lake 513.

Past experiences throughout the Cordillera Blanca and accumulated scientific knowledge indicated that Lake 513 was extremely dangerous in 1988 (Kaser and Osmaston 2002; Reynolds 1992; Reynolds et al. 1998). To prevent an imminent outburst flood, engineers installed a siphon that pumped approximately 1 million m^3 of water out of Lake 513. But the lake level and freeboard did not diminish because new water entered the lake during the 1988–1989 wet season. Engineers thus installed a second siphon after securing private funding from Great Britain and Austria. Peru's 2,000 % inflation at the time, combined with intensifying Shining Path terrorist activities in the region, made work at the remote lake challenging and cumbersome. Nevertheless, by June 1990, the lake's water level had been lowered 5 m. A plan to lower the lake level much further was proposed, but before these measures were implemented Lake 513 produced a GLOF in 1991. The flood was alarming but relatively small thanks to previous engineering efforts that averted catastrophe. The GLOF undoubtedly would have been significantly larger if engineers had not already partially drained the lake. As predicted (HIDRANDINA 1988; Oberti 1973), the GLOF originated when glacial ice slid into the lake. Displacement waves 2 m high overtopped the moraine dam and initiated the outburst flood. Floodwater eroded a deep channel through the moraine, but, fortunately, water dissipated across the upper-valley floor near the lake and did not cause any loss of life in Carhuaz.

The 1991 GLOF motivated authorities to finance the final stage of the Lake 513 security project. The objective was to lower the lake level 20 m so that it was dammed behind bedrock instead of the moraine. However, the lead UGRH engineer had extensive experience previously directing the Lake Parón drainage project (completed in 1985) and understood that drilling a single tunnel 20 m below the Lake 513 water surface would have created a dangerous situation: upon opening the tunnel to drain the lake, the flowing water could have generated enough hydrostatic pressure to create a catastrophic flood. The lead engineer thus knew from the outset to drain Lake 513 carefully and slowly. With funds provided by the National Institute of Civil Defense (INDECI), engineers drilled four tunnels through the Lake 513 moraine dam and bedrock beneath it. Each tunnel was drilled below the other to lower the water level slowly. By April 1994, the Lake 513 security project was completed. Engineers had removed 4–6 million m^3 of water, and the final 155 m long tunnel brought the lake level down so it was dammed behind bedrock with 20 m of freeboard (INAGGA 1997; Kaser and Osmaston 2002; Reynolds et al. 1998).

From 1994 to April 2010, Lake 513 was categorized as safe, with a low probability of producing a GLOF event. Nevertheless, Lake 513, like other Cordillera Blanca glacial lakes, was monitored to ensure its stability. A UGRH analysis of Lake 513 in 1997 concluded that it was not dangerous due to the successful implementation of the 1988–1994 GLOF prevention projects (Electroperu 1997). An independent report (INAGGA 1997) reiterated this assessment of the dam's stability but suggested that climate change—with the ensuing influence on glacier retreat and ice stability—increased the likelihood of glacier avalanches on Mount Hualcán. Because avalanches were impossible to predict, the report concluded, the only way to protect Carhuaz residents was through hazard zoning. The suggestion was never implemented. A few years later, a ten-year strategic development plan for Carhuaz did not even mention glacier hazards. It thus did not recommend any future hazard zoning to protect populations by directing future settlement or land use outside the areas exposed to potential GLOFs and avalanches (CEDEP and Carhuaz 2004). INDECI (2004), on the other hand, noted that there were risks of GLOFs, avalanches, and floods in the Chucchun River valley in Carhuaz, but the report indicated that Lake 513 was unlikely to produce a GLOF due to previous engineering projects. Residents, authorities, and UGRH engineers all believed Lake 513 remained safe—that is, until the April 2010 avalanche and flood.

4.3 Physical aspects of the 2010 avalanche and GLOF

At approximately 8 am on 11 April 2010 a rock-ice avalanche involving bedrock material detached from the steep SW slope of Mount Hualcán (6104 m above sea level [masl]), starting at an altitude of about 5400 m (see Figs. 1, 2 and 3). Based on pre- and post-event

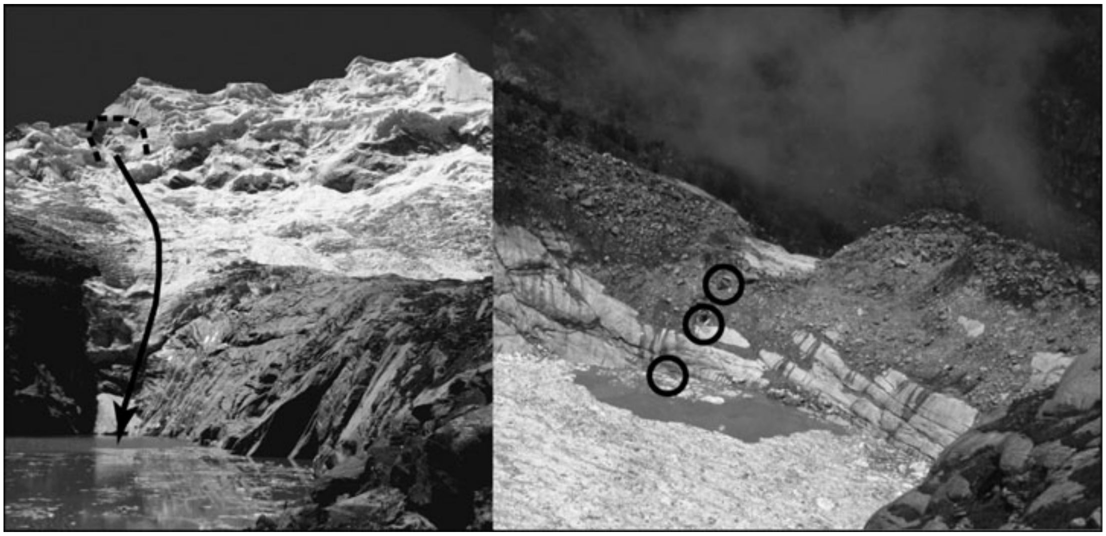

Fig. 2 Mount Hualcán (left) seen from Lake 513. Dashed line indicates the failure zone of the 11 April 2010 avalanche and the arrow the track of the avalanche impacting the lake. Lake 513 bedrock dam (at right) with overlying moraine material that was overtopped by wave generated by the avalanche impact. The breach in the moraine material formed by the overtopping wave is clearly visible at center. Circles indicate the location of the artificial drainage tunnels installed in the early 1990s

high-resolution satellite images and terrestrial photographs, the volume of the avalanche is estimated between 200,000 and 400,000 m^3. The avalanche travelled over the steep surface of Glacier 513 into Lake 513 at 4428 masl. The lake was impacted by the avalanche along its longitudinal axes. Despite the 20 m freeboard at the time of the April 2010 avalanche,

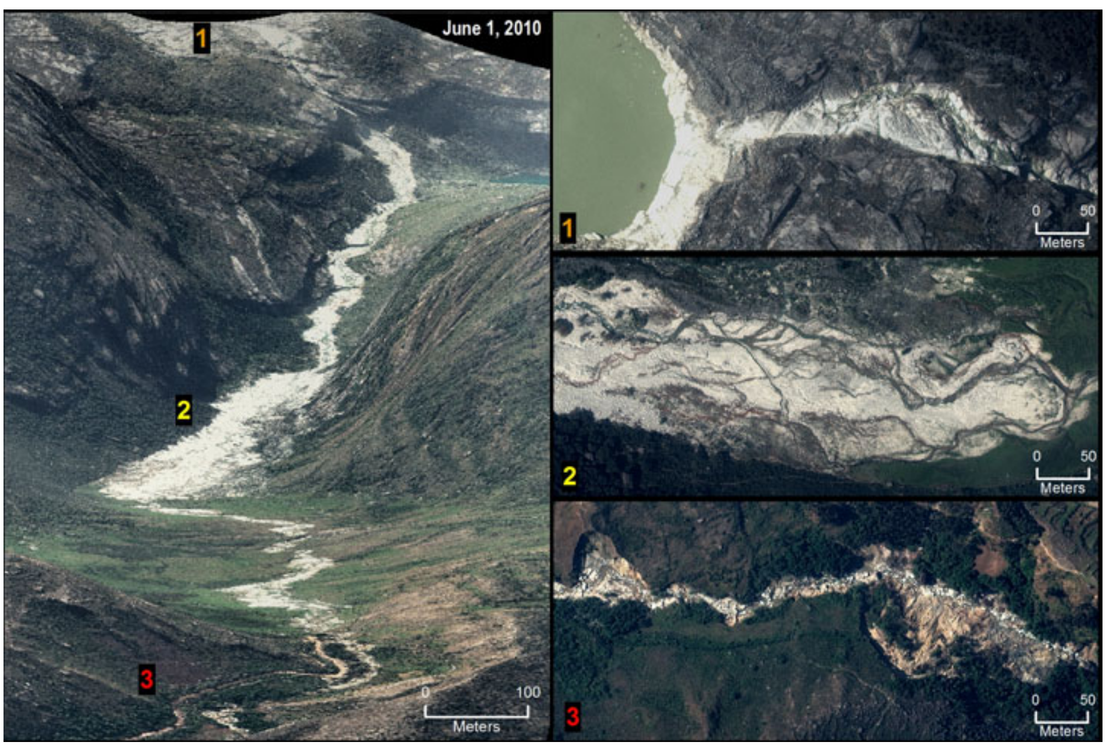

Fig. 3 GLOF transformations from 1) erosion of loose morainic sediments, 2) deposition of sediments on pampa, to 3) intensive erosion and sedimentation

the impact of the avalanche caused the bedrock dam to be overtopped. It is suggested that the avalanche impact caused a “push-wave” that moved the entire lake volume in a strong simultaneous displacement. The total wave height reached 25 m above the lake surface and washed the moraine material on top of the bedrock dam away (Haeberli et al. 2010).

The overflowing volume of water may have been on the order of<1 million m^3 and ran down glacially polished bedrock in the steep upper part of Hualcán Canyon. Erosion in loose morainic sediments started at an altitude of about 4100 masl, with deposition occurring in the upper part of the flat Pampa de Chonquil around 3650 masl. Its further trajectory intensively eroded the steep parts of Chucchun River below the Pampa de Chonquil. The flow thus transformed into a debris flow with higher sediment concentration and different flow rheology (see Fig. 3). Eventually, the outer parts of the city of Carhuaz were reached and an extraordinary peak flow in the Chucchun River and Santa River in the main valley persisted for about 16 h, covering 0.689 km^2 of land based on field survey and satellite images. This repeated transformation of the flood is not unusual for either GLOFs or large, mixed ice-rock avalanches (Cenderelli and Wohl 2003; Huggel et al. 2005). Flow transformations depend on a number of factors, including flow volume, channel gradient and width, availability and grain size distribution of sediment. In terms of hazards, flow transformations can be critical as they exert an important effect on the extent of affected areas.

The avalanche detached from Mount Hualcán’s southwest slope, a high mountain flank covered by steep glaciers and firn. Exposed bedrock in the detachment zone is present at elevations below ~5500 masl. Field surveys showed that both bedrock and glacier ice was involved in the avalanche, which thus formed a combined rock-ice avalanche. Slope failures in glacierized mountains are typically a result of a long-term predisposing factors and short-term triggers. Rock strength and structure, or slope geometry are among the predisposing factors while permafrost degradation can gradually reduce the shear strength of a slope, and earthquakes but also rapid (melt) water infiltration act as triggers of slope failures (Huggel et al. 2010). The exact attribution of a specific slope failure to the different factors controlling failure is extremely difficult, even with advanced mechanical slope stability models (Fischer et al. 2010). However, it is often possible to identify important processes driving slope instability. This also applies to the rock-ice avalanche from Hualcán. The slope at the detachment zone is inclined at ~40° and rock type is granodiorite.

To better understand the thermal conditions of the steep glacier ice that failed and to assess whether permafrost may exist in bedrock, we analyzed regional climate data. Long-term quality checked climate data are scarce in the Cordillera Blanca. However, for our purpose we are primarily interested in data of recent years on mean annual air temperatures (MAAT) at high altitudes. Feasible MAAT data were derived from long-term and short-term meteorological stations between 3000 masl and 5000 masl, as described in Georges and Kaser (2002), Juen et al. (2007), Racoviteanu et al. (2008), as well as from five additional temperature measurements, taken by UGRH for subsequent years in the 2000s, at sites between 4100 and 4800 masl within a distance of about 50 km of Hualcán (see Tables 1 and 2). A simple linear regression of elevation versus MAAT indicates a lapse rate of 0.65°C/100 m (with a coefficient of determination (R^2) of 0.98), which is in agreement with other studies (e.g. Juen et al. 2007) (see Fig. 4). Using this data and lapse rate, we estimate a MAAT of −2.5°C±0.5°C at 5400 masl, the elevation of the failure site of the 11 April 2010 avalanche. Based on that, the mean annual ground surface temperature (MAGST) of exposed bedrock at this site with a southwestern aspect is expected to around −2 to 0°C (Gruber et al. 2004; Huggel 2009), i.e., in conditions of warm permafrost. However, if we consider the three-dimensional topography, a strong

Table 1 Temperature changes in the Cordillera Blanca and adjacent regions over the past decades

Region/meteorological station	Observation period	Temperature change cumulative; rate	Reference
Tropical Andes, 1°N-23°S, 279 stations	1939–2006	+0.68°C; 0.1°C/decade	Vuille et al. 2008b
Central Peru (9–11°S), including Cordillera Blanca, 29 stations at 20 to 4600 m asl	1951–1999	+1.95°C; 0.39°C/decade	Mark and Seltzer 2005
	1962–1999	+1.01°C, 0.26°C/decade	
Huaraz, 3038 m asl	1970–1999	+2.79°C; 0.9°C/decade	Racoviteanu et al. 2008
Recuay, 3394 m asl	1970–1999	+1.55°C; 0.5°C/decade	Racoviteanu et al. 2008
Lamalto, 4030 m asl	1970–1999	+0.93°C; 0.3°C/decade	Racoviteanu et al. 2008

thermal flux from the northern side towards the failure site is likely. From thermal modeling studies it is known that such ridge situations are characterized by complex thermal flux fields (Noetzli et al. 2007), in this case probably resulting in somewhat higher MAGST than estimated above. A further thermal perturbation comes from steep polythermal glaciers which can warm bedrock up to 0°C. Complex thermal ground conditions, such as those most likely found at the Hualcán failure site, have been observed at a number of other failure locations of large ice and rock avalanches in Alaska, the Caucasus, and the European Alps (Haeberli et al. 2004; Huggel 2009).

Recent climate change in the Cordillera Blanca has primarily been reported in terms of increasing temperature: several studies provide evidence of warming in the Cordillera Blanca over the past decades, but give different numbers for the rate of warming (Table 1). Racoviteanu et al. (2008) indicated a rate of temperature increase of 0.3-0.92°C/decade over the period of 1970–1999 for stations between 3000 and 4000 masl, while Mark and Seltzer (2005) found a rate of warming of 0.26°C/decade (1962–1999) for stations of the Cordillera Blanca and adjacent low-elevation areas. Over larger regions of the tropical Andes, including high-elevation sites, an increase of temperature of ~0.1°C/decade over the past 50–70 years has been reported (Bradley et al. 2009; Vuille et al. 2008b). Studies on the influence of recent warming on the high-elevation firn, ice, and bedrock ground temperatures are missing in the Cordillera Blanca, but are likely similar as found in other regions of the world. Especially relevant for slope stability is the decreasing strength of steep ice at higher ice temperatures with possible transformation of cold to temperate ice, as well as more frequent melting processes reducing shear strength at the base of steep glaciers (Huggel 2009), and generally decreasing slope stability in relation with warming and thawing permafrost (Gruber and Haeberli 2007).

Table 2 Additional reference values for estimates of mean annual air temperatures (MAAT) at high elevations

Meteorological station; distance to Hualcán	Observation period	MAAT	Reference
Artesonraju, 4811 m asl; 28 km	2004, 2007–09	1.8°C	This study
Jarhuacocha, 4076 m asl; 125 km	2005–09	6.6°C	This study
Uruashraju, 4693 m asl, 49 km	2005–08	2.7	This study
Yanamarey, 4698 m asl; 58 km	2004–05, 2008–09	2.1°C	This study
Vallunaraju, 5000 m asl, 26 km	2000–01	0–0.7°C	Georges and Kaser 2002
Querococha, 3980 m asl, 62 km	1965–1994	6.5°C	Juen et al. 2007

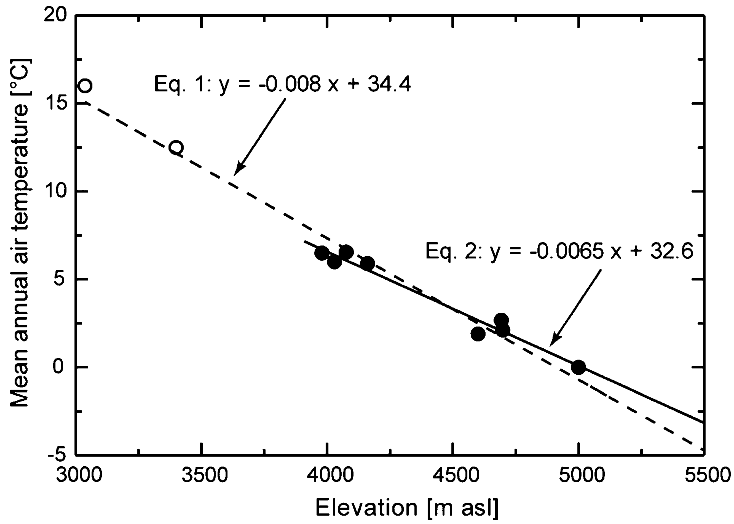

Fig. 4 Data from regional meteorological stations on mean annual air temperature (MAAT). Two linear regression equations are computed, with Eq. 1 including data from lower elevation stations (open circles, 3000–3400 masl) and high elevation stations (>4000 masl), and Eq. 2 including only data from above ~4000 masl (filled circles). Coefficients of determination (R^2) are in both cases 0.98. For the extrapolation of MAAT to the failure site of the April 2010 avalanche from Hualcán at 5400 masl, we used Eq. 2 in order to avoid climatic disturbance effects from the valley location of the lower elevation stations. Reference for data is provided in Tables 1 and 2

In addition to long-term warming, seasonal and diurnal temperature variations, in particular maximum temperatures, can affect slope stability in glacierized high-mountain areas. Huggel et al. (2010) found that many slope failures in rock and ice around the world were preceded by particularly warm periods days and weeks before failure. The critical point is air temperatures above freezing, implying melting and infiltration of liquid water into bedrock cleft systems and at the base of steep glaciers. We analyzed temperature records at Yanamarey and Artesonraju stations at 4698 m and 4811 masl, respectively, ten days before the 10 April 2010 rock-ice avalanche from Hualcán. These stations are located 28–58 km from Hualcán and might provide an approximation of the local temperatures at Hualcán, although the horizontal thermal homogeneity at higher elevations found in the tropics (Juen et al. 2007) might be less valid for shorter time periods of hours and days. Both temperature records show that maximum temperatures were consistently above freezing up to 10 days before failure, reaching up to 8°C at 5400 masl (extrapolated). While such temperature conditions are probably not unique in the Cordillera Blanca, it is likely that it implied melt water infiltration into rock clefts, with a destabilizing effect due to processes such as hydrostatic pressure variations, refreezing at night with volume expansion, or reduction of cohesion in ice-filled clefts (Hasler et al. 2011).

While this analysis does not directly allow any attribution of the April 2010 slope failure to climate change effects, it should emphasize the possible role of increasing temperatures for slope stability in temperature-sensitive glacierized mountain regions such as at Hualcán. Risk reduction and adaptation measures must be able to cope with the currently prevailing uncertainties related to limited knowledge of climate change effects on high-mountain slope stability, in particular in terms of timing and location of slope failures. It is worth noting that climate change effects on slope stability in cryosphere environments can thereby be effective over the long-term (e.g. decade- to century-scale glacier retreat and debuttressing effects) or short-term (e.g. very warm periods), and are typically overlaid on predisposing geological, topographic, and other factors that determine the basic susceptibility of slopes to failure (Allen et al. 2010; Huggel et al. 2010). In 2010 and 2011 several other rock-ice avalanches were observed in the Cordillera Blanca, with seeming higher frequency than during past decades. Although the historic documentation is incomplete and these recent slope failures have not yet been studied in detail, they could be heralds of upcoming increased slope instabilities which would be of particular concern, given the many glacial lakes in the Cordillera Blanca that are prone to avalanche impacts.

4.4 Societal impacts of the 2010 GLOF

The 11 April 2010 GLOF generated by the Hualcán avalanche had significant impacts on downstream households, infrastructure, agriculture, and livestock (see Figs. 1, 3, and 5). During the actual flood and its immediate aftermath, widespread panic consumed the area and a state of emergency was quickly declared in the communities of Acopampa, Pariacaca, Hualcán, and Obraje (INDECI 2010a). Because the peak flow of the flood lasted for 16 h, and it damaged or blocked several local roads and the major highway linking Carhuaz to the rest of the region, there was significant uncertainty about the nature of the event and the likelihood of further avalanches or flooding. Initial media reports indicated that a number of people were missing or had perished, though these turned out to be incorrect. A preliminary INDECI (2010b) report issued on 11 April estimated that the GLOF affected the life and health of 100 people and either damaged or destroyed 22 houses, 90 % of the city's water system, 100 km of highway, 110 km of irrigation canals, 35 ha of land directly, and 690 animals. The GLOF also affected a much broader population through damages to key infrastructure such as the major highway in the Santa River valley, smaller connecting roads, several bridges, and the disruption of public services. A follow-up report was issued by INDECI (2010a) later in the day that revised the direct damage estimates. It stated that

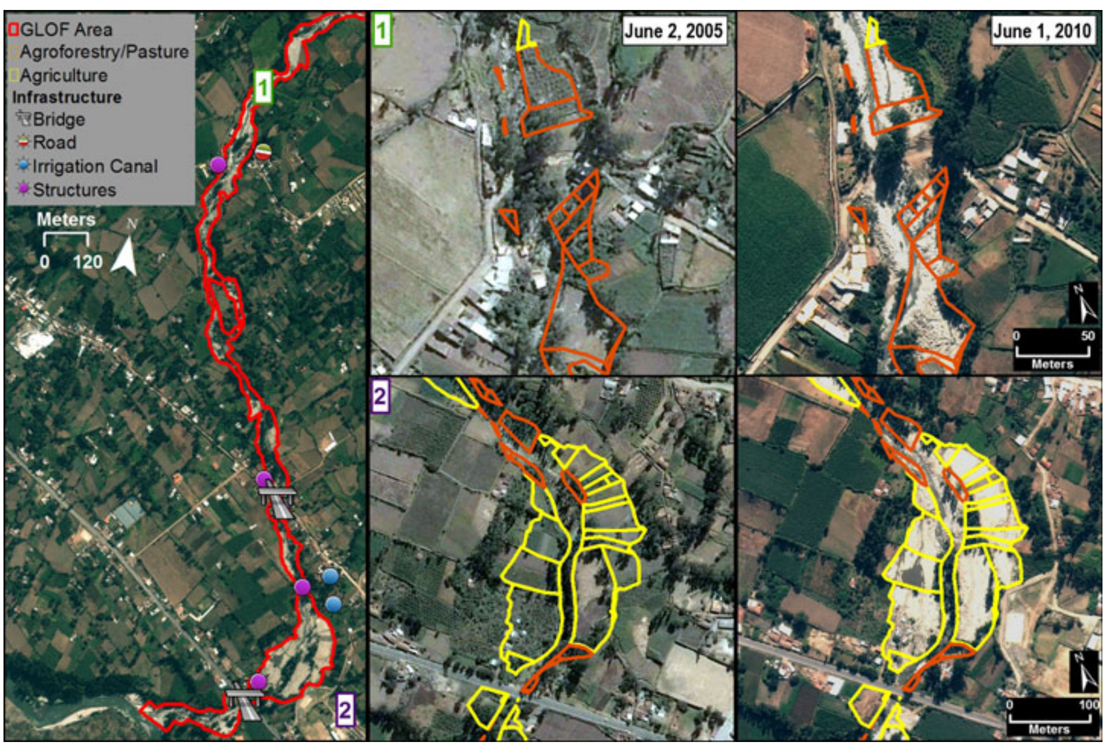

Fig. 5 Area flooded and infrastructure impacted by 11 April 2010 Lake 513 GLOF, with comparative representation of flooded area before and after event

the life and health of 100 people had been affected, eight structures had been damaged, three bridges had been damaged or destroyed, and the potable water system had been affected. In the immediate aftermath of the event, government authorities from the National Food Assistance Program (PRONAA) delivered 1.2 metric tons of food and supplies to households most affected by the debris flow and heavy machinery began to clear debris and repair roads.

In order to examine both the direct and indirect social effects of the GLOF, field research was conducted during July 2010 to examine the consequences of the GLOF on the local population. Research methods utilized in the study included spatial analyses using satellite imagery, a complete survey of the affected area with local inhabitants and government representatives, key interviews with government and civil society representatives, and unstructured household interviews with 10 people impacted by the GLOF (see Section 3 for more information). Household interviewees were selected using a convenience sample and the overall interview population represents 10% of the total population classified by INDECI as either directly "affected" or "victims." Overall, the spatial analyses of satellite imagery, key interviews, and household interviewees illustrated the extent and magnitude of the GLOF's impacts on household livelihood production strategies and factors influencing human exposure and vulnerability to the event.

The entire GLOF event affected .689 km^2 of land along the Chucchun River and damaged infrastructure such as the regional water system, roads, bridges, and irrigation canals (see Fig. 5). The extent of the affected area was digitized using post-GLOF 1 m resolution Digitalglobe satellite imagery (red areas in Figs. 1 and 5). On the Chonquil Pampa, the flood wave destroyed the municipal water collection system that served 90 % of Carhuaz and the community of Acopampa; it had been constructed without completing a risk assessment (INDECI 2004, 2010a). Municipal potable water service to these communities was interrupted for 15 days, and fresh water supplies had to be delivered by vehicle to emergency distribution points throughout the region. The flood wave also damaged or blocked four vehicle bridges. One small wood footbridge that was not included in the INDECI revised report was also destroyed. Unpaved roads were damaged in a number of places due to flooding and landslides. INDECI (2010a) indicated that the GLOF destroyed 100 km of roads. The post-GLOF imagery analysis indicated that only 2.69 km of unpaved roads were either damaged or destroyed and one large landslide occurred. However, because the flood damaged key access points in the regional road network, it eliminated access to 20 km of unpaved roads above the city of Carhuaz and temporarily blocked the regional highway that links all of the cities in the Santa River valley. Finally, the flood damaged or destroyed approximately three kilometers of irrigation canals, including the intakes for the Savior de los Afligados and Tauripampa canals, both of which are important regional irrigation networks. Because the intake points for both canals were destroyed, and large quantities of sediments flowed into the canals before they were destroyed, INDECI's estimate that 110 km of canals were affected is most likely accurate.

In the immediate area of the water and debris flow, household-level impacts included the complete or partial destruction of houses and structures. According to INDECI's (2010b) final evaluation, 25 structures were affected by the GLOF, which is an accurate assessment. In addition, agricultural landholdings, agroforestry reserves, and livestock were also affected by the event, largely due to significant erosion of banks along the Chucchun River, landslides, and the mixed debris flow of the floodwaters. Analyses of the post-GLOF satellite imagery, parcel data from the Peruvian government, and field interviews illustrated that approximately 5 ha of irrigated crop lands and 6 ha of agroforestry and grazing lands were directly affected by erosion or debris deposition. Figure 5 illustrates the actual parcels that were affected in the lower reaches of the watershed and they are coded according to the way households utilized them in the production of their livelihoods (orange for agroforestry, yellow for agriculture). However, because the major canals that serve the area in the upper watershed were damaged and many smaller canal networks closer to the Chucchun River were also damaged or destroyed, the indirect and longer-term agricultural impacts of the flood on agricultural productivity will likely be much higher. Finally, interviewees confirmed that a large number of animals perished in the flood. Several thousand trout were killed in one aquaculture farm and hundreds of chickens, guinea pigs, pigs, and cows perished in the event. Interviewees further indicated that the flood not only affected the extent and quantity of their current agricultural and livestock holdings, but that the heavy deposition of barren and rocky sediments near the Santa River and the interruption of irrigation water has affected the longer-term productivity of their lands.

The sudden occurrence of the GLOF and the proximity of land, crops, animals, and people to the debris flood clearly demonstrate societal exposure to natural hazards. Yet other real and perceived factors further influenced their vulnerability. According to interviews with local government authorities, the glaciers and lakes were not being actively monitored and residents were not alerted until after the peak floodwaters had already passed through the region. Interviewees affected by the GLOF indicated that they had only a few moments to react and that the debris flow sounded like a "jet airplane" as it descended the Chucchun watershed. Local government representatives also indicated that the event could have been much more disastrous if the flood had been larger or the volume of water in the lake was higher. Longer-term factors affecting human vulnerability to the event include the presence of houses and infrastructure along the banks of the river, despite the fact that it has been repeatedly classified as an area of high risk by a number of government agencies (e.g. INDECI 2004). According to interviewees in the lower watershed, land resources are held by individual property owners up to the banks of the river. Economic capacity was identified as another factor influencing vulnerability in the area as many of the houses closest to the river that were damaged or destroyed belonged to recent immigrants to town or older residents with few resources. The affected areas utilized for agriculture, agroforestry, livestock grazing, or aquaculture were identified by interviewees as critical resources for household livelihood activities and the generation of income. The factors influencing the presence of people, structures, agriculture, and animals in such high risk areas, according to interviews with local government authorities, include a lack of communication with local residents about the risks present in the area, the absence of effective public safety programs, high levels of poverty, and the failure of municipal authorities to enforce local zoning regulations.

5 Socio-environmental framework for glacier hazard management

Analysis of this Cordillera Blanca case study—the 40 years of studies, projects, and policies at Mount Hualcán, Lake 513, and Carhuaz—makes it possible to qualitatively evaluate long-term glacier hazard management. We examine which measures were successful or unsuccessful and explain how or why certain measures were implemented or omitted. Our evaluation is based on an idealized conceptualization of risk reduction and adaptation. Risk is characterized by the likelihood of a natural hazard occurring and the degree to which people are exposed and vulnerable. Adaptation involves actual adjustments made in response to observed or predicted changes in the climate system. Thus the ideal glacier hazard management approach—and, more broadly, an ideal disaster risk reduction and climate change adaptation program—would involve various socio-environmental components: having perfect knowledge to identify and predict hazards emerging from environmental change; reducing the likelihood of those events taking place through appropriate engineering strategies; removing all exposed populations, property, and infrastructure from potential hazard zones; and decreasing vulnerability through political and socio-economic measures that enhance resilience. While impossible or impractical to achieve all of these, these combined elements provide a standard against which to evaluate the actions that were actually implemented or omitted.

The following socio-environmental framework (Fig. 6) stems from this idealized vision of glacier hazard management. Examining the 40 years of glacier hazard management, we identified periods or actions that most reduced or increased the risk of glacial hazards. We also explain why certain decisions were made or challenged, why policies were created or resisted, and why projects were implemented or not. The analysis thus involves not just identifying what was done to reduce glacier disaster risk, but also explaining why it was or was not implemented. The framework has two components. First, it identifies the most significant drivers and controls that either facilitated or impeded glacier hazard management in this specific case study. These actions are listed in Fig. 6 as either implemented or omitted in this Cordillera Blanca case. Second, it takes the specific factors that were implemented or omitted and generalizes them into broader categories that either reduced risk and facilitated adaptation or increased risk and impeded adaptation. These conditions are listed as either facilitators or impediments in Fig. 6. The empirical evidence and this corresponding framework enrich the understanding not only of long-term disaster risk reduction and climate change adaptation, but also the limits of adaptive capacity and resilience (Adger et al. 2009a, b; Arnell 2010; Eakin and Lemos 2010; Gardner and Dekens 2007; Orlove 2009).

5.1 Factors facilitating risk reduction and adaptation

(1) **Technical Capacity**. Although UNISDR and other researchers underscore the ways in which disasters are more socio-economic and political than "natural" (Lavell and Franco 1996; Maskrey 1993; Steinberg 2000; White 1974; Wisner et al. 2004), risk nonetheless involves the physical environment that generates the flood, avalanche, or earthquake. Consequently, science, technology, and engineering play vital roles in disaster risk reduction, as well as in climate change adaptation. Environmental

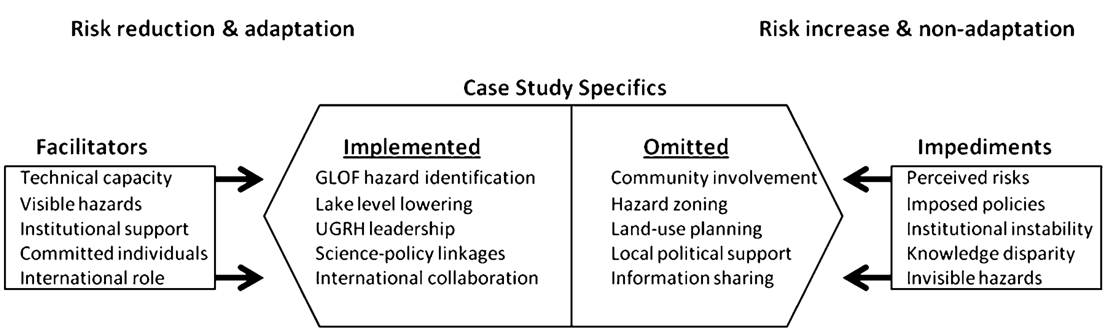

Fig. 6 Integrated socio-environmental framework identifying factors that facilitate or impede disaster risk reduction and climate change adaptation. The broader facilitators and impediments are drawn from the specific conditions or actual actions that were implemented or omitted in the Cordillera Blanca case of glacier hazard management at Mount Hualcán, Lake 513, and Carhuaz

knowledge, early warning systems, meteorological information, hazard maps, building materials, and building codes all help protect societies and reduce disaster impacts. In some cases of geoengineering and weather manipulation, however, technological solutions for climate change can turn out to be more harmful than beneficial (Fleming 2006; Harper 2008).

In the Cordillera Blanca, science and engineering contributed significantly to the monitoring, studying, and draining of dangerous glacial lakes to prevent GLOFs during the past half century. In fact, engineering efforts to partially drain and dam glacial lakes has been the single most successful strategy for reducing disaster risk and adapting to new environmental conditions (glacial lakes) created by glacier retreat and post-LIA climate change. Accumulated scientific expertise allowed experts first to identify Lake 513 as potentially dangerous in 1985 and then to detect the precise point in 1988 when it posed an *imminent threat*, not just a potential hazard. This classification convinced engineers to initiate mitigation measures immediately. It also motivated the national government to devote resources to the project and persuaded private donors in England and Austria to support the lake drainage project. Imminent threats alone may not be enough to inspire emergency responses, but at Lake 513 the imminent threat was a critical factor driving the mitigation and adaptation project. The imminent threat, however, was only recognized because of technical capacity that involved environmental knowledge (science) and engineering experience.

This knowledge and experience was essential for safe and timely completion of the Lake 513 drainage project. By the 1980s, the UGRH had already designed and implemented a variety of engineering strategies to partially drain and dam more than 25 Cordillera Blanca glacial lakes (Ames 1998; Elías Pizarro 1962; Fernández Concha 1957; Lliboutry et al. 1977; Trask 1953; Zapata Luyo 2002). Building on this experience, experts recognized that they could minimize GLOF risk by immediately removing water from Lake 513 using siphons. Their experience also persuaded them to drain the lake slowly and safely using four progressively deeper drained tunnels. Without detailed knowledge and experience from other glacial lakes throughout the Cordillera Blanca, the Lake 513 mitigation project might have proceeded differently, possibly with catastrophic consequences. Relevant engineering practices, appropriate technologies, and specific local knowledge thus all facilitated glacier hazard management and proved enormously successful. Nevertheless, the occurrence of the 2010 GLOF suggests that knowledge was not complete and risk had not been completely eliminated with technical capacity.

(2) **Disaster Events with Visible Hazards.** Disaster mitigation programs are often reactive rather than preventative because early warning systems, building codes, hazard zoning, and other risk reduction measures are frequently implemented only after catastrophes (Amendola et al. 2008). Direct experiences with disasters can thus inspire new programs to reduce risk. Additionally, some people are more likely to support climate change adaptation initiatives if they have had direct experiences with natural disasters (Whitmarsh 2008). Visual clues that clearly identify natural hazards are also more likely to affect people's acknowledgement of risks and their likelihood of embracing disaster risk reduction programs (Burningham et al. 2008). But these risk perceptions based on visibility and experience can never be divorced from other factors, such as environmental conditions, economic constraints, political forces, social relations, or cultural values.

In the case of Cordillera Blanca glacier hazard management, the combination of disaster events and the presence of a visible threat created a sense of urgency to implement GLOF prevention projects. But the experience and visibility of potential avalanches and outburst floods affected authorities, decision makers, and experts more than the local population who calculated risk differently (as discussed below). The most decisive advances in glacier hazard management in the Carhuaz, Mount Hualcán, and Lake 513 areas occurred in the immediate wake of avalanches and floods in 1970, 1991, and 2010. The 1970 earthquake and Yungay avalanche inspired the first systematic studies of Mount Hualcán glaciers and led to the innovative but failed hazard zoning plans to reduce future exposure to potential glacier avalanches and GLOFs. The visible precariousness of the Lake 513 moraine dam compelled engineers both to initially drain the lake using siphons in 1988–1989 and to later design the four-tunnel approach for lake drainage (Reynolds 1992; Reynolds et al. 1998). The 1991 Lake 513 GLOF had a notable impact on the completion of the lake drainage project because the flood justified funding for the project and it was implemented soon after. Local officials also supported lake drainage projects in the aftermath of the 1991 event, and one Carhuaz mayor even became known as a "friend of the lake" for his support of disaster prevention projects, but only in the immediate aftermath of the GLOF that visibly exposed the hazard. More recently, the April 2010 GLOF event stimulated notable responses from UGRH engineers, local residents, Carhuaz authorities, and international experts. Public town meetings and workshops revealed a surge of support for studies and proposals to address Mount Hualcán and Lake 513 hazards. Unfortunately, the local political support and involvement has not continued with concrete community contributions; nor have local residents seemed willing to discuss hazard zoning as a way to reduce disaster exposure by restricting future settlement and construction within potential floodplains.

Visible hazards—and the corresponding publicity that often follows—can inspire authorities to respond to some degree. They will be held more accountable if the hazard is known and public awareness spreads. Coverage of the 2010 GLOF, for example, was widespread, with newspaper articles, satellite images, photographs, blog discussions, and amateur videos of the floodwaters circulating on the Internet. The UGRH also conducted a new study of Lake 513 and held an international meeting related to climate change and glacier hazard issues more broadly (Haeberli et al. 2010). The Lake 513 case reveals that experience with disaster events and observable hazards can inspire management responses, though they do not always convince local residents of the need to protect themselves from natural hazards because these residents face a number of risks and make decisions based on a complicated calculus of various risk perceptions (Carey 2008). In none of these cases were Carhuaz residents motivated to move out of exposed floodplains and potential avalanche paths, which would have of course involved substantial costs and impacts on their livelihoods.

(3) **Institutional Support.** Social scientists have paid increasing attention to governance and institutional capacity in their analyses of climate change (Adger et al. 2009a, b; Eakin 2006; Okereke et al. 2009). Institutions drive or hinder adaptation processes because their presence (or absence) shapes decision making and project implementation. In many cases, however, there tends to be a sluggish relationship between the scientific findings related to disaster risk or climate impacts and the institutional responses to those findings (Eakin and Lemos 2010; Paton et al. 2010).

The UGRH and its various antecedents dating back to the original Lakes Commission in 1951 were critical drivers of glacier hazard management because they possessed key personnel, experience, knowledge, equipment, and funding to carry out successful glacier hazard management. The UGRH discovered Lake 513—and dozens of other unstable glacial lakes—in 1980 because it routinely monitored Cordillera Blanca glaciers and lakes. The institution provided logistical consistency and helped channel national and international resources toward completion of the lake drainage project. Even if the UGRH lacked adequate resources and technical personnel during the late 1980s and early 1990s, a skeleton institution was far more successful at implementing GLOF prevention projects than no institution at all.

Financing is another critical role that institutions can play by both providing funds in the first place or by directing them to specific projects from diverse sources. While the UGRH lacked adequate resources to immediately drain Lake 513 in 1988, it nonetheless utilized its existing budget provided by the Peruvian government, the national energy company Electroperú, and the Callejón de Huaylas engery company HIDRANDINA to detect and address the Lake 513 GLOF risk during the 1980s. First, institutional resources were critical in the early 1980s to support investigations that discovered Lake 513 and monitored its dangerous growth. Then, UGRH resources helped fund the installation of siphons at the lake in 1988 and 1989, which removed a significant volume of water from the lake and thereby minimized destruction from the 1991 GLOF. Even when funds were cut drastically during the country's economic catastrophe in the late 1980s, some GLOF prevention work at Lake 513 continued because of institutional momentum (HIDRANDINA 1988, 1990). The UGRH's institutional apparatus also facilitated the channeling of international funds from Britain and Austria to the Lake 513 project in 1989, which helped make up for declining government or energy company support for glacier hazard management while the Peruvian economy and state floundered in the late 1980s and early 1990s.

(4) **Committed Individuals.** Individuals can play powerful roles in disaster risk reduction and climate change adaptation, even as responses are shaped by global forces and an increasing number of local, national, and international stakeholders. The initiation and implementation of projects depends on successful publicity, funding, technical expertise, management, and public support. All four of these aspects require, or significantly benefit from, committed individuals who go beyond their regular duties to advocate vigorously for specific projects and agendas. In the Cordillera Blanca, several committed individuals exhibited four particular skills that facilitated glacier hazard management: technical expertise, leadership/institutional diplomacy, fundraising, and community outreach. At distinct points between 1970 and 2010, specific individuals relied on these skills to implement measures that reduced the risk of glacier disasters (see Kaser and Osmaston 2002; Morales 1972; Portocarrero 1980, 1995; Reynolds 1992; Reynolds et al. 1998).

First, technical expertise came from training, knowledge, and experience in glacier hazard management throughout the Cordillera Blanca and abroad. On one level, this expertise allowed scientists and engineers to identify Mount Hualcán glacier hazards during the early 1970s and later discover and monitor the development of Lake 513 during the 1980s. The UGRH engineers who led efforts to implement Carhuaz hazard zoning in the 1970s and who also monitored, drained, and dammed Lake 513 during the 1980s and 1990s had experience in the Cordillera Blanca since the 1960s. A British geoengineer and University of Innsbruck glaciologist also offered critical technical insights into the Lake 513 GLOF prevention project based on their Peruvian and international experience with glacier hazards. They helped recognize the impending danger from the lake in 1988, urged the use of siphons to drain it quickly, and then recommended the slower drainage strategy with four successive tunnels that was completed in 1994 (Kaser and Osmaston 2002; Reynolds et al. 1998). Second, leadership and institutional diplomacy was important for achieving the significant expansion of glacier hazard management initiatives during the early 1970s, which required government support and funding. This was also when the glacier experts persuaded the government to implement hazard zoning in Carhuaz. Although it ultimately failed due to local opposition, hazard zoning represented an innovative glacier hazard management initiative and was spearheaded by UGRH directors and engineers who worked to secure regional populations (e.g. Morales 1972; Portocarrero 1980). These engineers kept UGRH projects moving forward during Peru's late-1980s socio-economic and political crises, often due to tireless advocacy for risk reduction programs and by building international collaborative relationships. Third, fundraising efforts also helped reduce GLOF risks, and this is especially important in a developing country like Peru. Some Peruvian engineers followed bureaucratic channels to acquire funds, even during the late 1980s budget shortfalls, from UGRH oversight agencies. Foreign experts pursued informal fundraising through their embassies and among donors for the emergency purchase of the second siphon installed at Lake 513 in 1989 (HIDRANDINA 1990). Fourth, publicity and community outreach was important for glacier hazard management. The glaciology division director boosted public and political support for the institution during the 1970s (Bode 1990). To raise public and expert awareness of glacier hazards and climate change, the UGRH director also held public town meetings, gave public presentations, and organized a scientific workshop following the 2010 Lake 513 GLOF. Without these motivated and active individuals, GLOF prevention projects at Lake 513 may have languished or failed. Their contributions to disaster risk reduction transcended specialized knowledge and technical skills as they exploited whatever power, political connections, and resources they could to win public support and advance project completion.

(5) **International Involvement.** At certain points, international assistance helped advance glacier hazard management. The 1970 UNESCO scientific assessment of Cordillera Blanca glaciers and glacial lakes provided part of the scientific basis for the Carhuaz relocation and hazard zoning policies attempted during subsequent years (Lliboutry et al. 1970). International experts again provided critical support in 1989 when government funding for the Lake 513 drainage project evaporated (HIDRANDINA 1990). The issue of global warming that has galvanized public and scientific interest since the 1980s has also brought more international attention to Andean glacier hazards, including from the European experts involved with the initial Lake 513 drainage project in the late 1980s (Kaser and Osmaston 2002; Reynolds et al. 1998). In July 2010, an international workshop held in Carhuaz concerning Lake 513 and Mount Hualcán glacier hazards demonstrated a collaborative relationship among local residents, regional authorities, Peruvian engineers, and foreign experts. International contributions to Cordillera Blanca glacier hazard management since 1970 thus helped reduce disaster risk and promoted initiatives to lessen the potential impacts of glacier retreat and related GLOF hazards on local societies. Yet research elsewhere (Anderson 2009; Harper 2001; Sundberg 1998) also demonstrates how international scientists and experts can co-opt local agendas or perpetuate colonial and postcolonial power imbalances. International involvement, then, is not always beneficial to all stakeholders. International participation can thus facilitate disaster risk reduction and climate change adaptation as it did with Lake 513 GLOF prevention, but the inherent power discrepancies that exist among stakeholders in the developing and developed world could lead to the privileging of certain segments of the population over others in risk reduction and adaptation efforts.

5.2 Factors impeding risk reduction and adaptation

Until recently, research examining impediments to climate change adaptation focused on three broad areas: ecological or physical limits, technological limits, and economic limits. But Adger et al. (2009a, b) demonstrate that these factors are too narrow because they fail to consider endogenous factors and do not address the powerful role of risk perceptions, culture, ethics, and knowledge. Orlove's (2009) study of international responses to glacier retreat focuses on other issues that can derail successful adaptation, including the "multiple impacts problem" and the "responsibility problem." Qualitative analysis of glacier hazard management in the Lake 513 case reveals additional factors beyond these issues that can thwart disaster risk reduction and climate change adaptation. These impediments in this case include endogenous societal forces and limitations on scientific knowledge while also including Orlove's broader issues of responsibility and diverse impacts.

(1) **Perceived Risks.** Poor and marginalized populations are generally the most vulnerable to natural disasters and climate change (Brooks et al. 2005; Eriksen and Kelly 2007; Steinberg 2000; Wisner et al. 2004). They tend to get pushed into exposed areas, receive the fewest government protections, and lack resources to prevent catastrophe or recover afterward. Yet vulnerable populations should not be construed as passive victims unable to change or respond to the effects of climate change. Nor will they simply embrace all new measures designed even for well-intentioned disaster risk reduction or climate change adaptation. Instead, all vulnerable populations—whether U.S. entrepreneurs or Peruvian indigenous people—consist of complex individuals who rank risks and weigh the potential impacts of adaptation programs on their social standing, property, livelihoods, economic opportunities, values, worldviews, and daily behavior (Etkin and Ho 2007; Jurt 2009; Paton et al. 2010; Slovic 1999). In the case in glacier hazard management in Carhuaz, some residents viewed new risk reduction and adaptation measures with skepticism or even disdain because they imposed new risks on them, such as decreased social (class and race) status, loss of identity, eviction from homelands, diminished political autonomy, or infringements on values and cultural emblems.

    This discrepancy in perceived risks among locals and policy makers was a major reason for failed Carhuaz hazard zoning in the 1970s. Residents were not convinced the government would reimburse them for their property losses and pay for the relocation. Further, the principal groups targeted for relocation in 1970 were the upper and middle class residents who lived on alluvial plains at the confluence of the Santa River and its tributaries flowing from Cordillera Blanca glaciers. But after the 1970 earthquake, many urban survivors believed rural indigenous people were "invading" the cities and towns to loot damaged properties and "steal" disaster aid such as food and clothing, which the wealthier urban residents believed was not meant for the rural indigenous population (Bode 1977; Doughty 1999; Oliver-Smith 1986; Stein 1974; Walton 1974). Relocation of Carhuaz to an area outside the hazard zone not only threatened individuals but also the town's political-economic position more broadly. Many in Carhuaz feared that the time-consuming process of moving and reconstructing Carhuaz would give the neighboring town of Marcará the opportunity to displace Carhuaz as the administrative and economic center of the region (Walton 1974). Others opposing the relocation of Carhuaz lamented the loss of specific places within the urban area that might not be reconstructed in the relocated site: the Carhuaz market, churches, schools, sports fields, government offices, and other public buildings. These structures not only served utilitarian purposes; they also provided the community with a sense of place and stood as emblems of the town's financial, administrative, and cultural hegemony within the province (Vinatea Quevedo 2002). Hazard zoning thus created several new risks for community members: economic and material losses, declining social (race and class) standing, and abandonment of homelands.

These perceived social, political, and economic risks associated with hazard zoning and community relocation outweighed any gains residents saw from the reduction of avalanche or GLOF risk. In an ideal glacier hazard management agenda, populations would have moved outside potential flood and avalanche paths to minimize their exposure to these hazards. Variation in perceived risks thus impeded successful glacier hazard management because people opposed hazard zoning and remained exposed to future GLOFs, such as the 1991 and 2010 floods from Lake 513. Carhuaz residents who rejected glacier hazard management plans, however, were adapting to a different set of social, economic, and political changes seen as more pressing than environmental changes.

(2) **Imposed Government Policies.** Differences in risk perceptions are important because defining risk is in itself an act of power: the way risk is framed simultaneously suggests certain solutions to reduce risk (Slovic 1999). Local responses to natural hazards and climate change must thus be situated within the broader political contexts that inform decision making and risk perceptions (Jurt 2009). Additionally, people often reject information about hazards and do not take scientific assessments or government warnings at face value when risk reduction or adaptation initiatives threaten their autonomy (see above; Paton et al. 2010). Local residents may even oppose well-intentioned plans to reduce risk when such measures are imposed from above or undermine local autonomy and power (Buchenau and Johnson 2009).

As discussed, many urban Callejón de Huaylas social groups viewed government hazard zoning plans as imposed policies from Lima that threatened their authority (Bode 1990; Oliver-Smith 1986). They favored other policies such as the highly successful policy to drain glacial lakes throughout the Cordillera Blanca. But they believed hazard zoning was a political tool that President Juan Velasco's military government (1968–1975) utilized to manipulate Peruvian society. Carhuaz merchants, landowners, and ruling classes feared that relocation would fulfill Velasco's broader objective of creating a more egalitarian society by empowering farmers and indigenous residents (Peru 1971). Because government authorities and engineers did not first consult Carhuaz residents about relocation plans, the policy appeared to be an imposed agenda meant to take land from wealthier populations and give it to the poor (Walton 1974). Moreover, local and regional authorities never embraced hazard zoning or pursued disaster prevention policies, thereby leaving glacier hazard management in the hands of national government agencies and individuals that locals historically distrusted. Some Carhuaz residents even believed scientific assessments of Mount Hualcán glacier hazards were imposed on them (Carey 2010). They thus hired their own scientists to conduct glaciological studies (Morales 1972). When these scientists disagreed with the glaciology division, residents' distrust of the national government escalated and they rejected relocation. Imposed policies thus impeded glacier hazard management because populations remained exposed to glacier hazards. In 2010, however, the UGRH took steps to approach Lake 513 and Mount Hualcán hazards through public dialogue, discussion, and involvement of Carhuaz residents and authorities alongside UGRH engineers. Efforts to communicate openly with communities and avoid top-down policymaking may facilitate long-term disaster risk reduction and climate change adaptation.

(3) **Institutional Instability.** While effective institutions can enhance adaptive capacity, institutional instability or weak institutions can stifle disaster risk reduction and climate change adaptation (Eakin and Lemos 2010). A lack of funds for equipment, projects, and personnel, as well as the absence of technical oversight and project guidance, can derail specific projects and limit the invention of creative solutions. In the Cordillera Blanca, the UGRH supported hazard zoning in the 1970s. Moreover, its successful lake drainage projects in the late 1980s and 1990s likely prevented a catastrophic GLOF. But institutional instability and weakness slowed project completion and has led to increased disaster risk over time. Management of the UGRH shifted seven times among five different state agencies between 1973 and 1990, thereby continually altering the agency's mission, eroding public support, and causing funding shortages (Carey 2010). The lack of continuous budgets had significant effects on glacier hazard management. When the UGRH was under HIDRANDINA in the late 1980s, for example, its annual operating budget fell from US $437,663 in 1986 to US $53,512 in 1990, even though hazards remained (UGH 1990). The institution then lacked equipment and personnel to conduct long-term glaciological and climatological studies (HIDRANDINA 1988, 1990). Institutional instability thus led to a diminished capacity for technical, scientific, and mitigation measures—and the lake drainage period dragged on six years from 1988 to 1994. More widespread government instability also affected popular opinions of the glaciology division and government projects more broadly. In the last four decades, the Peruvian national government has gone through elected democracies, authoritarian military governments, and the self-declared auto-coup of Alberto Fujimori during the 1990s. These changes have eroded public confidence in state agencies, including the glaciology division, thereby increasing vulnerability to glacier hazards.

(4) **Knowledge Disparity.** Knowledge disparity refers to limited knowledge and scientific uncertainty as well as divergent knowledge systems that distinct social, ethnic, or racial groups possess. The disparity thus pertains to knowledge about both human and environmental systems. Adaptation under scientific uncertainties is a major subject and under intensive discussion (Dessai and Hulme 2007; Füssel 2007). For the physical systems determining GLOF hazards, we distinguish two different sets of knowledge level and related uncertainties in terms of degree of uncertainty, timing, and magnitude of processes. The first set of uncertainty refers to glacier retreat and lake formation and growth. Research has documented twentieth-century Cordillera Blanca glacier retreat and glacial lake formation, especially for the last three decades, but with relatively little information on previous periods (Georges 2004; Mark and Seltzer 2005; Racoviteanu et al. 2008; Silverio and Jaquet 2005). Inventories of current location and extent of glaciers and glacial lakes are available at UGRH. Juen et al. (2007) furthermore assessed potential future changes in runoff from glaciers based on IPCC scenarios, but spatially explicit data on future glacier retreat are lacking. In the Alps, methods are now developed to project the sites of future glacial lakes using techniques of different complexity to assess ice thickness and detect glacially overdeepened areas (Frey et al. 2010). This information implies some uncertainty as to the timing and actual formation of glacial lakes. Nevertheless, it is useful for expanding scientific knowledge and could be applied to the Cordillera Blanca. The first set of uncertainty thus can be characterized by a comparably low degree of uncertainty, with precise knowledge on current extent of glaciers and glacial lakes, and techniques available to indicate approximate timing and dimensions of future glacier retreat and lake formation and growth.

Higher degrees of uncertainty exist for the second type of knowledge, which is related to slope instabilities such as rock slope failures, ice avalanches, moraine failures, or combined events. Limited knowledge exists because of scarce climatic, glaciological, and geological data in the Cordillera Blanca on the one hand, and a generally limited understanding of the stability of steep ice and bedrock on the other hand. It is known that both long-term gradual warming and climatic extremes (both temperature and precipitation related) can have impacts on slope stability in temperature-sensitive glacier and permafrost environments (Gruber and Haeberli 2007; Huggel 2009; Huggel et al. 2010). However, prediction of the exact location and timing of slope failures is virtually impossible. As a consequence, impacts from rock-ice avalanches on glacial lakes, such as was the case at Lake 513, are difficult to predict, and combine with additional uncertainties related to the stability of glacial lakes (Hegglin and Huggel 2008; McKillop and Clague 2007). Therefore, knowledge is limited with respect to location and timing of potential GLOF events. Within a socio-environmental framework for adaptation and risk reduction, a way to cope with different levels of prevailing uncertainties is an improved monitoring program that considers environmental change as well as social, political, and institutional conditions.

Important knowledge disparities also exist across human systems. As discussed, institutional instability, shifting power dynamic, changing social relations, and varying risk perceptions by different groups are difficult to predict and thus can impede the implementation of appropriate adaptation measures. In the early 1970s, the extent of local opposition to hazard zoning was not recognized in advance because no one could predict the social conflict that emerged in the aftermath of the earthquake and Yungay avalanche, which unleashed highly contested class and racial politics in the region (Bode 1990; Oliver-Smith 1986). In 1988 and 1989, when experts suggested warning locals about a possible Lake 513 GLOF, authorities and some Peruvian engineers discarded the idea because it was unclear how locals would respond—whether they would take the early warning seriously or whether it would trigger resentment and rejection of government projects or engineering strategies. The long-term institutional instability and corresponding shifts from authoritarian to democratic governments created circumstances in which local residents often, but not always, distrusted authorities. Over time, international forces such as neoliberalism or environmental activism also affected Peruvian government programs, making it difficult or impossible to predict future trends and priorities among stakeholders. There is little effort, overall, to model human behavior, as opposed to environmental processes, even ones as complex as global climate and circulation, in part because human systems are so complex, which is to say unpredictable or uncertain. Thus, uncertainty about human systems may be even more significant as an impediment to glacier hazard management than limited knowledge about natural hazards or the lack of high resolution data for downscaling climate models.

There is also disparity among diverse residents about what constitutes appropriate knowledge to rely on for decision making. In the 1970s, for example, some Carhuaz residents distrusted UGRH assessments of Mount Hualcán glacier hazards and instead hired their own independent, non-government engineer (Morales 1972). When he contradicted UGRH engineers and concluded that glacier hazards did not exist, Carhuaz residents' distrust of the national government and skepticism about hazard assessment increased. The result of such suspicion emerging over competing claims to accurate knowledge hindered glacier hazard management because residents subsequently rejected hazard zoning—and found themselves inhabiting the potential flood path along the Chucchun River after Lake 513 expanded dangerously in the 1980s. There are other aspects of knowledge discrepancies, such as local beliefs about enchanted lakes or place naming in the Lake 513 area. Many Callejón de Huaylas residents do not approach some Cordillera Blanca lakes for fear that spirits could either suck them in or provoke a flood to inundate an individual or community (Stein 1961). The place name for the area just below Lake 513 is "Acopampa," which is a plain where a "floury drink" (aco) was deposited, or flooded (CEDEP and Carhuaz 2004). Both of these examples reflect alternative views of potential lake hazards that differ significantly in expression from Western scientific explanations. Enchanted lakes compel some to stay away from lakes, while it is possible that Acopampa became the place name because a GLOF once deposited its sandy or floury liquid on the valley floor. Overall, knowledge disparity can generate uncertainty or distrust, even in cases where there is potential to augment existing information through the incorporation of local knowledge (Cruikshank 2005).

(5) **Invisible Hazards.** Even when potential climatic and hazard threats are identified, experienced, or communicated to the general public, people often do not alter their behavior to protect themselves (Burningham et al. 2008; Whitmarsh 2008). Research suggests that when hazards can be easily conveyed through traditional photographs, they are easier for the general public to comprehend than normal plan view maps, 3D maps, or aerial photographs (Haynes et al. 2007). Visible hazards, especially when combined with disaster experiences, can thus enhance compliance with risk reduction and adaptation agendas. But the converse is also true: invisible hazards, even when known and communicated to the public, are more likely to generate complacence than observable hazards. There are thus two aspects of invisible hazards: first, invisible to the public even though scientists have identified them and, second, unidentified hazards. At Lake 513, GLOF hazards received relatively little attention between 1994 and 2010, in part because the freeboard was large (20 m) and the lake did not visibly demonstrate dangerous conditions. Instead, the hazard existed underneath the glacial ice high above the lake on Mount Hualcán. In this case, then, the post-1994 hazard was both unknown and invisible, giving local residents and authorities, as well as engineers, the impression that the lake was secure. Ideal glacier hazard management would have continued scientific studies to understanding the changing environment and the evolution of new hazards while also striving to keep minimizing human exposure and reducing vulnerability.

6 Conclusions and perspectives

This interdisciplinary investigation of 40 years of glacier hazard management on Mount Hualcán, at Lake 513, and in Carhuaz helps illuminate long-term processes of comprehensive disaster risk reduction programs and adaptation to the effects of post-LIA climate change that influenced glacier retreat and glacial lake formation. The empirical case reveals a largely successful example of glacial lake hazard identification and lake drainage projects at Lake 513. These initiatives minimized the impacts of GLOFs in 1991 and 2010. But government efforts to reduce exposure to glacier hazards in the 1970s largely failed because residents rejected hazard zoning. Moreover, with the rock-ice avalanche from Hualcán, the 2010 GLOF event had a trigger that has been known from cases in other regions of the world but whose impact was not fully accounted for in the risk reduction measures at Lake 513. As outlined here, slope failures of rock and ice often have a thermal component, such as long-term climate change or short-term temperature variations. However, while it is likely that the high temperatures during the days preceding the Hualcán slope failure had some influence on the avalanche, as for most other such slope failures, a direct attribution to climate change cannot be made.

The qualitative analysis of these processes of actual glacier hazard management since 1970 reveals that some initiatives to reduce risk and adapt to the effects of climate change on glacial lake hazards were successful and implemented, while others were rejected or omitted. The case thus allows the identification of various factors that either facilitated or impeded glacier hazard management. We present these factors not only as case-specific variables affecting glacier hazard management, but also as a broader socio-environmental framework for disaster risk reduction and climate change adaptation. While this case illustrates these factors as the most significant, other related forces such as public pressure, the media, social inequality, and limited financial resources may also impact the course of disaster risk reduction and climate change adaptation.

The specific drivers and controls presented in this integrated socio-environmental framework demonstrate how collaboration across the natural and social sciences can lead to holistic understandings of disaster risk reduction and climate change adaptation. Climate models suggest future decades will bring pronounced, if not dramatic changes in glacierized high-mountain regions such as the Cordillera Blanca. Changes may be beyond the historical experience of local people. Projections suggest that some existing glacial lakes will experience further growth, while others will form at new locations as glaciers continue to retreat. Similarly, slope instabilities are likely to develop at new locations and may pose a serious threat if impacting glacial lakes—just as the 2010 event has shown. To adequately address and manage emerging risks, adapted strategies will need to be developed. Such strategies must consider the risks posed by environmental changes and related hazards, as well as the social, cultural, political and institutional systems. This paper shows a way forward to link these social and environmental systems by analyzing the main factors that facilitated or hindered the implementation of successful glacier hazard management strategies.

The next step is to build new adaptive strategies based on these factors—strategies to identify new and existing hazards and to reduce human vulnerability to glacier hazards over the long term. There is thus a need to expand the analysis of potential GLOF hazards from the lower glacier margin and glacial lake dam to avalanche starting zones near mountain summits above lakes. Long-term development agendas and community planning should strive to keep people outside potential flood and avalanche paths. Relocation of existing settlements may not be practical, but minimizing future exposure through land use planning could help reduce risk. More research on the socio-economic costs of such development plans is necessary, though most climate and hazards research tends to be done by natural not social scientists. It is also vital to communicate hazard information to local people through education and access to updated information, especially given the diversity of perceived risks in the region. Installation of early warning systems may reduce disaster impacts in the event of a future GLOF or avalanche. It may be necessary in this Carhuaz case to construct a retention dam at the lower end of the Pampa de Chonquil. Many of these suggestions require additional research and historical insights from this paper help illuminate where challenges and successes may lie.

This case of long-term glacial hazard management has implications well beyond Cordillera Blanca glacier hazards because the adaptive strategies outlined here also apply to other cases of climate change adaptation and disaster risk reduction. The facilitators and impediments presented for this case likely affect responses to droughts and hurricanes or sea level rise and epidemics. In the Andes in particular, the projected water shortages from climate change and glacier retreat will increasingly affect inhabitants in small communities and cities such as Lima, La Paz, and Quito (Bradley et al. 2006; Juen et al. 2007; Kaser et al. 2003; Mark et al. 2005). If water management plans evolve without recognition of the various variables presented above—or if they are carried out only among scientists, engineers, and policymakers without community involvement—then effective adaptation measures will likely be difficult to achieve. Implementing effective adaptive strategies will require an integrated approach that involves an array of residents and stakeholders while building on enhanced knowledge of coupled socio-environmental systems.

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